

VERIFICATION

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The undersigned declares further that all statements made herein of his/her own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

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DESCRIPTION

SURFACE-COATED CUTTING TOOL

Technical Field

5 [0001] The present invention relates to a cutting tool, such as a throw-away insert or drill, equipped with a coating layer on a substrate surface.

More specifically, the present invention relates to a surface-coated cutting tool with superior lubricity that is suited for cutting copper and the like.

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Background Art

[0002] Examples of widely known cutting tools include throw-away inserts used for turning and milling as well as end mills generally used for side milling, beveling, and fluting various types of metals, and drills used for boring.

15 These end mills and drills are formed with a section that includes a cutting section, known as the body, and a section known as the shank that is mounted in a drive device. Examples of bodies include: solid bodies, where the body is formed integrally from a cutting section and a support that includes a flute for supporting the cutting section and allowing chips to be ejected; brazed bodies,
20 where the cutting section is brazed to the support; and throw-away bodies, where the cutting section can be attached to and removed from the support. Conventionally, solid bodies are formed from high-speed tool steel or cemented carbide. Brazed bodies are formed by brazing a cutting section formed from a

hard material such as cemented carbide to a support formed from high-speed tool steel.

[0003] In recent years, various cutting tool materials have been developed to meet the demand for higher efficiency and precision in cutting. In

5 the process of developing these materials, ceramic coating technology, in which a coating layer formed from ceramics is applied to the surface of a tool substrate, has become a crucial technology in cutting tools. For example, the

use of titanium-based ceramics, e.g., titanium carbide (TiC), titanium nitride (TiN), titanium carbonitride (Ti(C,N)), and oxide-based ceramics, e.g., alumina

10 (Al₂O₃) and zirconia (ZrO₂) to form coating layers for cutting tools used in high-speed, high-efficiency operations involving high speeds and high feeds is widely known. Patent Document 1 describes a throw-away insert equipped

with a coating layer with a defined X-ray diffraction index of orientation. This insert is used in high-speed, high-efficiency operations involving high speeds

15 and high feeds. In addition to throw-away inserts, this type of ceramic coating technology is also becoming widely used in solid and brazed tools that are often used in end mills and drills.

[0004] The inclusion of a ceramic coating on a cutting tool improves surface hardness and heat resistance and allows the tool to handle high-speed,

20 high-efficiency operations involving high speeds and high feeds. In addition to this type of high-speed, high-efficiency operation, in recent years attention has been given to methods that protect the environment such as mist cutting, where the use of cutting oil is drastically reduced, or dry cutting, where cutting

oil is not used. To handle these types of operations, throw-away inserts equipped with a coating layer with superior welding resistance or a coating layer with a chip sliding feature (see Patent Document 2 and Patent Document 3), and a drill coated with a CrN film having lubricity (Patent Document 4) have been proposed. In addition, cutting tools equipped with an aluminum nitride coating layer for improved heat dissipation and the like have been proposed (see Patent Document 5 through Patent Document 12).

[0005]

[Patent Document 1] Japanese Laid-Open Patent Publication Number Hei 11-124672

[Patent Document 2] Japanese Laid-Open Patent Publication Number Hei 10-158861

[Patent Document 3] Japanese Laid-Open Patent Publication Number 2003-225808

[Patent Document 4] Japanese Laid-Open Patent Publication Number 2003-275911

[Patent Document 5] Japanese Examined Patent Publication Number Sho 59-27382

[Patent Document 6] Japanese Patent Publication Number 2861113

[Patent Document 7] Japanese Laid-Open Patent Publication Number 2002-273607

[Patent Document 8] Japanese Laid-Open Patent Publication Number 2002-263933

[Patent Document 9] Japanese Laid-Open Patent Publication Number 2002-263941

[Patent Document 10] Japanese Laid-Open Patent Publication Number 2003-19604

5 [Patent Document 11] Japanese Laid-Open Patent Publication Number 2003-25112

[Patent Document 12] Japanese Examined Patent Publication Number Sho 59-27302

10 Disclosure of Invention

[0006] However, all of the conventional cutting tools described above have insufficient lubricity, especially for mist cutting and dry cutting, in which no cutting oil is used. This leads to reduced tool life. Thus, there is a need to improve lubricity so that tool life can be extended. With end mills and drills in
15 particular, high lubricity is important for increasing the ability of chips to be ejected out through the flute formed on the body. High lubricity is also preferable for cutting materials that tend to weld and for deep hole boring, where the ability of chips to be ejected out is important.

[0007] The main object of the present invention is to provide a surface-
20 coated cutting tool with improved lubricity and extended tool life.

[0008] The present invention meets the objects described above by defining the composition of an outermost layer to contain predetermined elements so that lubricity is provided for the outermost layer, which makes

initial contact with the workpiece during cutting, and by defining the composition of the inner layer to improve wear resistance and fracturing resistance.

[0009] More specifically, the present invention provides a surface-coated cutting tool equipped with a coating layer on a substrate surface. The coating layer is formed from an inner layer formed on a substrate and an outermost layer formed over the inner layer. The outermost layer and the inner layer meet the following conditions.

<Inner layer>

10 The inner layer is formed from a compound formed from a first element and a second element, the first element being at least one element selected from a group consisting of a periodic table group IVa, Va, VIa metal, Al, Si, and B, and the second element being at least one element selected from a group consisting of B, C, N, and O (except if the first element is B by itself, the
15 second element must be an element other than B).

<Outermost layer>

The outermost layer is formed from aluminum nitride or aluminum carbonitride. The outermost layer contains more than 0 and no more than 0.5 atomic percent chlorine.

20 [0010] The present inventors investigated the interrelationships between coating layers and ways of improving coating layer properties in order to extend tool life even when a cutting tool is used in usage environments that impose harsh conditions, e.g., in the case of throw-away inserts used for

turning and the like, cutting operations that involve high temperatures for the cutting edge such as dry cutting, where no cutting oil is used, and intermittent cutting, and, in the case of drills and end mills, cutting operations such as mist cutting, dry cutting, boring, and cutting of workpieces that tend to easily weld.

- 5 As a result, it was found that tool life could be extended efficiently by using a coating film with superior lubricity as the outermost layer and forming the inner layer with films having a predetermined composition. More specifically, by forming the outermost layer from a film formed from aluminum nitride containing a predetermined amount of chlorine as described above, lubricity
- 10 can be provided even in cutting operations such as dry cutting, intermittent cutting, and boring. As a result, welding resistance is improved and the coating layer can be prevented from peeling. In the case of throw-away inserts used in the turning and the like: 1. the superior lubricity reduces the cutting force received by the tool and, also, fracturing resistance and wear resistance
- 15 can be improved by forming the inner layer from films having a predetermined composition; and 2. by using a film with superior lubricity, "shredding" of the workpiece surface after cutting due to contact with the cutting tool is reduced, thus providing high-quality, high-precision workpieces. Furthermore, in the case of drills and end mills: 1. the superior lubricity reduces the cutting force
- 20 received by the tool and improves ejection of chips and breakage resistance, while the use of a predetermined compositions for the films in the inner layer improves wear resistance, chipping resistance, and fracturing resistance; and 2. by using a coating layer with superior lubricity, the product quality can be

improved, e.g., the roundness of holes can be improved, thus providing high-quality and high-precision workpiece products. The present invention was defined based on these observations.

[0011] The improvement in tool life described above is currently believed

5 to be for the following reasons. The aluminum nitride film provides thermal stability and lubricity. Also, when an aluminum nitride film contains a predetermined amount of chlorine, in the case of cutting operations with throw-away inserts that tend to raise the temperature of the cutting edge, e.g., dry cutting and high-speed and high-feed cutting, a protective film is easy to
10 form on the tool surface when the cutting edge reaches a high temperature of approximately 900 deg C during cutting. This protective film can improve lubricity and is believed to improve the welding resistance of the tool. Also, by forming films from predetermined compositions for the inner layer, it appears that reduction of wear resistance can be avoided, thus making it possible to
15 provide a tool with both superior lubricity and superior wear resistance. With drills and end mills, the use of an aluminum nitride film containing a predetermined amount of chlorine is believed to reduce the friction coefficient between chips and areas associated with cutting (specifically, the tool surfaces at the cutting edge and the flutes). As a result, it is believed that, at the area
20 around the cutting edge, the work needed to generate chips is reduced and the chips are more easily ejected, leading to adequate tool life for cutting operations such as dry cutting, deep boring, and cutting of easily welded workpieces, while the quality and cutting precision of the workpiece is also

improved. It is also believed that by including a predetermined amount of chlorine in the outermost layer, in addition to the friction coefficient being reduced, the formation of a protective film on the tool surface becomes easier in cutting operations that tend to result in high temperature and high pressure for the cutting edge, e.g., dry cutting and deep boring. This protective film is believed to improve the lubricity of the tool so that the welding resistance of the tool is improved. Furthermore, it is believed that by forming the inner layer from films having predetermined compositions, it is possible to avoid reducing wear resistance so that a tool with both superior lubricity and wear resistance can be provided. The present invention will be described in further detail below.

[0012] (Coating layer)

<Outermost layer>

In the present invention, the outermost layer, which makes initial contact with the workpiece when performing a cutting operation, is formed from an aluminum compound such as aluminum nitride or aluminum carbonitride. Then, in the present invention, chlorine is included in this film formed from aluminum nitride. More specifically, more than 0 and no more than 0.5 atomic percent of chlorine is included in the outermost layer. The inclusion of no more than 0.5 atomic percent of chlorine in the outermost layer makes it possible for a protective film to form in high-temperature cutting environments, thus improving lubricity. If the chlorine content exceeds 0.5 atomic percent, the film forming the outermost layer can peel easily. If there is

- no chlorine, the protective film described above does not form. It would be especially preferable for the chlorine content to be at least 0.07 atomic percent and no more than 0.3 atomic percent. If a chemical vapor deposition (CVD) technique such as thermal CVD or plasma CVD to form the aluminum nitride
- 5 film containing more than 0 and no more than 0.5 atomic percent of chlorine in the outermost layer, the reaction gas can be a gas containing chlorine such as hydrogen chloride (HCl). In this case, the hydrogen chloride content can be more than 0 and less than 5.0 percent by volume, and more specifically no more than 1.0 percent by volume, where the entire reaction gas is defined as
- 10 100 percent by volume. If a physical vapor deposition (PVD) technique such as arc ion plating or magnetron sputtering is used to form the aluminum nitride film, chlorine ions can be implanted after the film is formed using ion implantation. The chlorine content in the outermost layer can be adjusted by controlling the amount of implantation as appropriate.
- 15 [0013] The outermost layer can further include oxygen. More specifically, in addition to aluminum nitride and aluminum carbonitride, the outermost layer can be formed as an aluminum oxynitride or an aluminum carbon oxynitride film. The inclusion of oxygen makes the protective film easier to form.
- 20 [0014] With this type of outermost layer, it would be preferable for the film thickness to be no more than $1/2$ the total film thickness of the inner layer described later. This allows the coating layer to provide a good balance between wear resistance and lubricity, e.g., for forming the protective film. If

the thickness exceeds $1/2$, the outermost layer becomes too thick, so that while superior lubricity is provided, wear tends to take place, possibly leading to shorter tool life. More specifically, if the cutting tool of the present invention is to be a throw-away insert, it would be preferable for the film thickness of the outermost layer to be at least 0.03 microns and no more than 10 microns. If the cutting tool of the present invention is to be a drill or an end mill, it would be preferable for the thickness to be at least 0.03 microns and no more than 8 microns. If the thickness is less than 0.03 microns, obtaining adequate lubricity becomes difficult. If the thickness exceeds 10 microns or 8 microns, the outermost layer becomes thicker than the inner layer, tending to reduce wear resistance as described above. Film thickness can be measured, for example, by cutting the cutting tool, e.g., an insert or drill with a coating layer, and observing the cross-section under an SEM (scanning electron microscope).

[0015] At the outermost layer, it would be preferable for the surface roughness at areas on the outermost layer near the ridge line of the cutting edge at areas that come into contact with the workpiece to have an R_{max} relative to a reference length of 5 microns of no more than 1.3 microns, where the roughness is measured by observing a cross-section of the cutting tool. Based on studies by the inventors, it was found that when the surface roughness of these contact areas of the outermost layers has an R_{max} that exceeds 1.3 microns, welding tends to take place with the workpiece, making it difficult to provide the advantages of lubricity. The surface roughness is measured by cutting the substrate after the outermost layer is formed,

performing lapping on the cross-section, observing the roughness on the film surface using a metallurgical microscope or an electron microscope, and determining the maximum surface roughness (R_{max}) within a reference length of 5 microns, thus eliminating macroscopic swelling and the like. Also, this surface roughness can be controlled to some degree through film forming conditions. For example, crystal structure becomes more coarse at higher film forming temperatures, and by extension there will be more surface roughness on the film surface. Thus, film forming temperature can be lowered to reduce surface roughness. Thus, R_{max} can be set to no more than 1.3 microns when the film is formed without requiring special treatment after film formation. However, it would also be possible to change surface roughness after film formation, e.g., by polishing with a buff, brush, barrel, elastic grindstone or the like, or by performing surface reforming through microblasting, shot peening, or ion-beam radiation.

[0016] <Inner layer>

The inner layer is formed from a compound formed from a first element and a second element, the first element being at least one element selected from a group consisting of a periodic table group IVa, Va, VIa metal, Al, Si, and B, and the second element being at least one element selected from a group consisting of B, C, N, and O (except if the first element is B by itself, the second element must be an element other than B). More specifically, films formed from compounds containing Ti such as TiCN, TiN, TiBN, and TiCNO and films formed from oxides such as Al_2O_3 and ZrO_2 provide superior wear

resistance and are preferable. Also, since TiN has good adhesion with the substrate, it would be preferable for it to be used as the innermost layer. The inner layer can be formed from a single film or can be formed from multiple films. If the inner layer is to be formed from multiple films, the films should have different compositions or structures. The inner layer can be formed either through CVD, e.g., thermal CVD or plasma CVD, or through PVD, e.g., arc ion plating or magnetron sputtering. The layer can be formed using widely known conditions.

[0017] By forming the inner layer with a Ti compound film as described above, superior wear resistance is provided. More specifically, a film formed from TiCN is suitable, and in particular it would be preferable to use a TiCN film with columnar structure. Furthermore, it would be more preferable to use a film formed from TiCN that has a columnar structure with an aspect ratio of at least 3, where an index of orientation (orientation intensity coefficient) TC(220), TC(311), or TC(422) of a crystal face (220), crystal face (311), and crystal face (422) respectively is the maximum index of orientation. By using a TiCN film with a structure having a predetermined shape and with a crystal face having a predetermined orientation, improved wear resistance and extended tool life can be provided even in harsh cutting environments, e.g., where the cutting edge reaches high temperatures.

[0018] The columnar structure is defined to have an aspect ratio of at least 3 because if the aspect ratio is less than 3, there tends to be reduced wear resistance under high-temperature cutting conditions. The desired wear

resistance is difficult to obtain with a granular structure.

[0019] A columnar structure can be formed, for example, if the film is formed using CVD, by using a raw gas that is an organic carbonitride that allows a columnar structure to be easily formed such as CH_3CN and by
5 controlling the reaction atmosphere temperature (at least 800 deg C and no more than 950 deg C) and pressure (at least 4.0 kPa and no more than 80 kPa). If a gas other than an organic carbonitride is to be used, the film growth rate can be increased, the film forming temperature can be increased, the concentration of the raw gas can be increased, or the like. An aspect ratio of at
10 least 3 can be achieved, for example, by reducing the average grain size of the crystal (preferably at least 0.05 microns and no more than 1.5 microns) and growing the film structure with a columnar structure. This can be done, for example, by appropriately adjusting the TiCN film forming conditions (film forming temperature, film forming pressure, gas composition, gas flow rate,
15 gas flow volume, and the like). It would also be possible to appropriately adjust the surface state of the substrate below or directly below the TiCN film or the surface state of the coating film located below or directly below the TiCN film. More specifically, it would be possible, for example, to control the surface roughness of the substrate surface to have an R_{max} (5 microns reference
20 length) to be at least 0.05 microns and no more than 1.5 microns and to form the TiCN film by appropriately changing the film forming conditions. Alternatively, it would be possible to control the surface roughness, chemical state, or grain diameter (preferably at least 0.01 microns and no more than 1.0

microns), or the like of a film, and to form the TiCN film on top of this film with the film forming conditions adjusted appropriately.

[0020] The aspect ratio described above can, for example, be measured in the following manner. A specular polish is applied to a cross-section of the

- 5 coating layer and the grain boundary of the structure of the columnar structure TiCN film is etched. Then, treating the widths of individual crystals parallel to the substrate at a position corresponding to 1/2 the film thickness of the TiCN film as grain sizes, the grain diameters of the crystals are measured and an average is calculated (the average is used as the average grain size).
- 10 The proportion of the average grain size relative to the film thickness is calculated by dividing the film thickness by the obtained average grain size, and this value can be used as the aspect ratio.

[0021] This TiCN film with a predetermined aspect ratio has the predetermined crystal orientations for the crystal faces as described. The index

- 15 of orientation TC is defined as follows.

[0022] [Equation1]

$$TC(hk1) = \frac{I(hk1)}{I_0(hk1)} \left(\frac{1}{8} \sum \frac{I(hk1)}{I_0(hk1)} \right)^{-1}$$

$I(hk1)$: measured diffraction intensity of the $(hk1)$ face; $I_0(hk1)$: average powder diffraction intensity based on JCPDS file of the carbide of the metal

20 forming the $(hk1)$ face and the nitride of the same metal; $(hk1)$: the eight faces (111), (200), (220), (311), (331), (420), (422), (511)

[0023] Making one of the indices of orientation (orientation intensity coefficient) TC(311), TC(220), or TC(422) be the maximum can be achieved by appropriately adjusting film forming conditions (film forming temperature, film forming pressure, gas composition, gas flow rate, gas flow volume, and the like) for the TiCN film. It would also be possible to appropriately adjust the surface state of the substrate below or directly below the TiCN film or the surface state of the film below or directly below the TiCN film. More specifically, for example, the TiCN film can be formed on a substrate that has been prepared with a surface roughness R_{max} (5 microns reference length) of at least 0.05 microns and no more than 1.5 microns, with the film forming conditions appropriately adjusted. Alternatively, for one of the films, the surface roughness, the chemical state of the grains, the grain size, or the like can be controlled, and then the TiCN film can be formed on top of this film with appropriately adjusted film forming conditions.

[0024] It would be preferable for the diffraction intensity to be measured for a flat section (smooth section) of the substrate so that surface indentations on the substrate do not create reflections. Also, the JCPDS file (Powder Diffraction File Published by JCPDS International Center for Diffraction Data) does not provide identification of X-ray diffraction intensity for carbonitrides of periodic table IVa, Va, VIa group metals. Thus identification of diffraction intensity for the TiCN film, which is one of these carbonitrides, can be obtained by comparing diffraction data for the carbide of titanium (Ti), which is the corresponding metal, diffraction data for the nitride of the same,

and the measured diffraction data for the TiCN carbonitride. Based on this, the face indices can be estimated, and the diffraction intensities for the face indices can be obtained.

[0025] If the inner layer is formed from multiple films, at least one of the
5 films can be the TiCN film with the predetermined aspect ratio and the like as described above, and the other films can be compound films formed from a first element and a second element as described above. The inner layer can, thus, be formed from this TiCN film and this compound film. The compound film can be a film having a composition different from that of the TiCN film or can be a
10 TiCN film having a structure or orientation that is different from this TiCN film. The TiCN film can be a single film or can be multiple films. Either the compound film or the TiCN film can be positioned closer toward the substrate. In other words, the structure, starting from the substrate side, can be the TiCN film, the compound film, the outermost layer, or can be the compound
15 film, the TiCN film, and the outermost layer.

[0026] If the cutting tool of the present invention is to be a throw-away insert, it would be preferable for the film thickness of the coating layer, formed from the outermost layer and the inner layer, to be at least 0.1 microns and no more than 30.0 microns. If the film thickness of the entire coating layer is less
20 than 0.1 microns, improved wear resistance becomes difficult to obtain. If the thickness exceeds 30.0 microns, the thicker coating layer improves wear resistance, but the increased hardness tends to increase fractures, leading to shortened tool life and making stable cutting difficult. If the cutting tool of the

present invention is to be a drill or end mill, it would be preferable for the film thickness of the coating layer, formed from the outermost layer and the inner layer, to be at least 0.1 microns and no more than 24 microns. If the film thickness of the entire coating layer is less than 0.1 microns, improved wear
5 resistance tends to become difficult to obtain. If the thickness exceeds 24 microns, the thicker coating layer improves wear resistance, but the peeling resistance and fracture resistance is reduced. This leads to frequent chipping, making stable cutting difficult.

[0027] It would be preferable for the outermost layer described above to
10 be formed with a film hardness lower than that of at least one of the films forming the inner layer. In other words, it would be preferable for the inner layer to include a film having a film hardness that is greater than that of the outermost layer. With an outermost layer having a low film hardness, it is possible to prevent fractures that occur when the tool initially engages with
15 the workpiece or in intermittent cutting. This makes it possible to provide stable cutting. In addition to changing film composition, film hardness can be adjusted by controlling the film structure through the film forming conditions. Given the same film composition, film hardness tends to be greater when the film structure is finer. The hardness of the films can be measured by cutting
20 the cutting tool with the coating layer, e.g., the insert or the drill, and measuring the hardness at the cross-section.

[0028] The coating layer coats at least the areas of the substrate surface associated with cutting. The coating layer can cover the entire substrate

surface. In the case of a throw-away insert, for example, the areas associated with cutting are the ridge line of the cutting edge, the rake face, and the flank face. In the case of an end mill or a drill, the area associated with cutting is what is generally known as the body, formed from a cutting section and a support. Fig. 1 (A) is a simplified front-view drawing of an end mill. Fig. 1 (B) is a simplified front-view drawing of a drill. More specifically, in the case of an end mill, the areas associated with cutting are, as shown in Fig. 1 (A): a cutting edge section formed from an end surface (an end cutting edge 1) and a side surface (a peripheral cutting edge 2); and a flute 3 that comes into contact with chips. Instead of forming the coating layer just on the body, it would also be possible to have the coating layer extend from a body 4, where the flute is formed from the end surface, to the section referred to as a shank 5 that is mounted in the driving device. In the case of a drill, the areas associated with cutting would be the tip 6 associated with the actual cutting and a groove (flute) 7 that comes into contact with the chips. With a drill as well, it would be possible instead of forming the coating layer only on a body 8 to extend the coating layer from the body 8, where the end and the flute are formed, to a shank 9 that is mounted in the driving device. For the areas where the coating layer is not to be formed, appropriate masking can be applied during film forming or polishing or the like can be performed after the film has been formed to remove the film.

[0029] Of course, after the coating film formed from the outermost layer and the inner layer are formed on the substrate surface, it would be possible as

in the conventional technology to apply surface treatment such as polishing or applying a laser to the ridge line of the cutting edge. With the cutting tool of the present invention, this type of surface treatment does not significantly reduce the characteristics of the coating layer.

5 [0030] (Substrate)

It would be preferable for the substrate of the present invention, especially the areas of the substrate associated with cutting, to be formed from a WC-based cemented carbide, cermet, high-speed steel, ceramic, a cubic boron nitride sintered body, or a silicon nitride sintered body. More specifically, if the
10 cutting tool of the present invention is to be a drill or an end mill, it would be preferable for at least the areas of the substrate associated with cutting to be formed from a WC-based cemented carbide, cermet, high-speed steel, or a cubic boron nitride sintered body. If a substrate formed from a WC-based cemented carbide or cermet is to be used, the advantages of the present invention will be
15 provided even if, on the substrate surface or the areas of the substrate surface associated with cutting, there is a reformed surface layer such as a "B-free layer" in which non-WC hardness phase has been removed, a binder-rich layer that is rich in binder and from which the hardness phase has been removed, or a hardened surface layer in which the binder phase has been removed.

20 [0031] The present invention can be implemented for various types of cutting tools such as drills, end mills, replaceable milling inserts, replaceable turning inserts, metal saws, gear cutting tools, reamers, and taps. In particular, the present invention is suited for throw-away inserts, drills, and

end mills. For drills and end mills, the present invention is used for solid drills and end mills, where the cutting section and the support are sintered or formed integrally, or for brazed drills and end mills, where the cutting section is brazed to the support, rather than throw-away (replaceable cutting edge) tools, where the cutting section and the support can be attached or removed. In the case of brazed tools, it would be preferable for the coating layer to be formed using PVD, which has a relatively low film-forming temperature. For solid tools, the coating layer can be formed using PVD or CVD, which has a relatively high film-forming temperature.

[0032] The surface-coated cutting tool of the present invention as described above is equipped with a predetermined coating layer. As a result, superior lubricity is provided as well as superior wear resistance, peeling resistance, fracture resistance, and breakage resistance. Thus, superior cutting properties and extended tool life can be provided even under usage environments involving harsh cutting conditions such as dry cutting, deep boring, cutting of workpieces that tend to weld easily, and other cutting operations such as high-speed, high-efficiency cutting where the cutting edge is exposed to high temperatures.

[0033] In particular, since the surface-coated cutting tool of the present invention is equipped with a predetermined TiCN film in the inner layer, both superior lubricity and superior wear resistance can be provided, and tool life can be extended with superior cutting characteristics even under the harsh usage environments described above.

Best Mode for Carrying Out the Invention

[0034] The embodiments of the present invention will be described.

[First example]

[0035] Using a throw-away insert for turning as an example, the present

5 invention will be described more specifically below.

(Test Example 1-1)

A powder with 86 percent by mass of WC, 8.0 percent by mass of Co, 2.0 percent by mass of TiC, 2.0 percent by mass of NbC, and 2.0 percent by mass of ZrC was prepared. The powder was wet mixed for 72 hours with a ball mill, dried, and then pressed into a green compact with a breaker structure. This green compact was heated for 1 hour in a vacuum atmosphere at 1420 deg C in a sintering furnace, resulting in a sintered body. SiC brush honing and beveling were performed at the ridge line of the cutting edge of the obtained sintered body, resulting in an ISO SNMG120408 throw-away insert formed from WC-based cemented carbide.

[0036] A coating layer was formed on the substrate surface using thermal CVD, a chemical vapor deposition technique. In this test, the following layers were formed, starting from the substrate side: an inner layer formed from TiN(0.5), TiCN(6), TiBN(0.5), κ -Al₂O₃(2); and an outermost layer formed from AlN(3). The numbers in parentheses indicate film thickness in microns. Table 1 shows an example of film forming conditions for each film. Specifically, the composition of the reaction gas (percent by volume), the pressure applied when forming the film (kPa), and the film forming temperature (deg C) are

shown. Film thickness was controlled by controlling the film forming time. Test samples in which the AlN film at the outermost layer have different chlorine contents were prepared by varying the film forming conditions as shown in Table 1. Table 2 shows chlorine content at the outermost layer.

- 5 Specifically, samples with more than 0 and no more than 0.5 atomic percent of chlorine, samples with more than 0.5 atomic percent of chlorine, and samples with no chlorine were prepared. Chlorine content was varied as shown in Table 1 by varying the proportion of hydrogen chloride (HCl) in the reaction gas. Also, using the amount of hydrogen chloride, the film forming pressure
- 10 and the film forming temperature were varied as appropriate. Furthermore, the surface roughness at sites on the outermost layer near the ridge line of the cutting edge at areas that come into contact with the workpiece were studied for test samples containing more than 0 and no more than 0.5 atomic percent of chlorine in the outermost layer. Observation of the tool cross-sections
- 15 showed that the Rmax for a reference length of 5 microns was no more than 1.3 microns for all samples. More specifically, the Rmax was 0.6 microns for Test Sample 1-2, for example. The chlorine content was measured using XPS (X-ray Photoelectron Spectroscopy), but composition can also be studied using micro-EDX (Energy Dispersive X-ray Spectroscopy) combined with a
- 20 transmission electron microscope or using SIMS (Secondary Ion Mass Spectrometry). Also, the Knoop hardness for each of the layers in the test samples was studied, and it was found that in all cases the outermost AlN film was harder than the inner TiCN film layer.

[0037] [Table 1]

Coating layer	Reaction gas composition (vol%)	Pressure (kPa)	Temperature (deg C)
AlN *1	AlCl ₃ :1.0 - 5.0%, NH ₃ :0.1 - 5.0%, N ₂ :20 - 50%, HCl:0.01 - 1.0%, H ₂ :rest	4.0 - 80	750 - 980
AlCN *1	AlCl ₃ :1.0 - 5.0%, NH ₃ :0.1 - 5.0%, N ₂ :20 - 50%, CH ₄ :0.5 - 5.0%, HCl:0.01 - 1.0%, H ₂ :rest	4.0 - 80	750 - 980
AlON *1	AlCl ₃ :1.0 - 5.0%, NH ₃ :0.1 - 5.0%, N ₂ :20 - 50%, CO ₂ :0.2 - 3.0%, HCl:0.01 - 1.0%, H ₂ :rest	4.0 - 80	750 - 980
AlN *2	AlCl ₃ :1.5%, NH ₃ :1.0%, N ₂ :40%, H ₂ :rest	5.0	1000
AlN *3	AlCl ₃ :1.5%, NH ₃ :3.0%, N ₂ :40%, HCl:5.0%, H ₂ :rest	13.3	950
AlON *2	AlCl ₃ :1.5%, NH ₃ :6.0%, N ₂ :40%, CO ₂ :1.0%, H ₂ :rest	6.8	1100
TiN	TiCl ₄ :2.0%, N ₂ :25%, H ₂ :rest	13.3	950
TiC	TiCl ₄ :2.0%, CN ₄ :5%, H ₂ :rest	13.3	1050
TiCN	TiCl ₄ :2.0%, CH ₃ CN:0.6%, N ₂ :20%, H ₂ :rest	6.7 - 80	800 - 950
ZrCN	ZrCl ₄ :1.0%, CH ₃ CN:0.6%, N ₂ :35%, H ₂ :rest	6.7	890
TiZrCN	TiCl ₄ :1.5%, ZrCl ₄ :1.0%, CH ₃ CN:1.0%, N ₂ :45%, H ₂ :rest	6.7	975
TiCNO	TiCl ₄ :2.0%, CO ₂ :2.5%, N ₂ :8%, H ₂ :rest	6.7	975
TiBN	TiCl ₄ :2.0%, BCl ₃ :5.0%, N ₂ :5.0%, H ₂ :rest	13.3	950
HfCN	HfCl ₄ :1.0%, CH ₃ CN:1.2%, N ₂ :40%, H ₂ :rest	6.7	1025
α Al ₂ O ₃	AlCl ₃ :2.0%, H ₂ S:0.3%, CO ₂ :5.0%, H ₂ :rest	6.7	1050
κ Al ₂ O ₃	AlCl ₃ :2.0%, CO ₂ :5.0%, CO:0.5%, H ₂ :rest	6.7	1000
ZrO ₂	ZrCl ₄ :2.0%, CO ₂ :7.0%, H ₂ :rest	6.7	1050
Al ₂ O ₃ -ZrO ₂	AlCl ₃ :1.5%, ZrCl ₄ :0.3%, CO ₂ :9.0%, H ₂ :rest	13.3	1070

*1: Chlorine content is more than 0 and no more than 0.5 atomic percent

*2: No chlorine

*3: Chlorine content is more than 0.5 atomic percent

5

[0038] [Table 2]

Test Sample No.	Outermost layer	Chlorine content (atomic %)
1-1	AlN *1	0.02
1-2	AlN *1	0.15
1-3	AlN *1	0.49
1-4	AlN *2	0
1-5	AlN *3	0.90

[0039] Using the surface-coated throw-away inserts with the outermost

layers as shown in Table 2, cutting operations were performed using the cutting conditions shown in Table 3. The cutting time involved in reaching the tool life was measured. In a peeling resistance test, cutting operations were repeated, with the end of tool life defined to be when flank face wear due to film peeling was at least 0.3 mm. In a fracturing resistance test, intermittent cutting was performed, with the end of tool life defined to be when a fracture occurred. The results of the tests are shown in Table 4.

[0040] [Table 3]

	Peeling resistance test	Fracture resistance test
Workpiece	S15C rod 3-sec repetition test	S45C fluted rod
Speed	V=300m/min	V=260m/min
Feed	f=0.3mm/rev.	f=0.2mm/rev.
Cutting depth	d=1.0mm	d=1.5mm
Cutting oil	None	None

10 [0041] [Table 4]

Test sample No.	Cutting time (min)	
	Peeling resistance test	Fracture resistance test
1-1	40	23
1-2	63	30
1-3	52	21
1-4	10	7
1-5	9	4

[0042] Based on the results, in the Test Samples 1-1 through 1-3, which have aluminum nitride layers with more than 0 and not more than 0.5 atomic percent of chlorine on the outermost layer as shown in Table 4, superior lubricity and improved welding resistance was observed even in environments where the cutting edge reaches high temperature, such as in dry cutting and

intermittent cutting. This provided superior peeling resistance as well as superior fracturing resistance due to reduced cutting force. Also, these Test Samples 1-1 - 1-3 showed reduced wear, indicating superior wear resistance. Based on these factors, it can be seen that the Test Samples 1-1 - 1-3 provide
5 longer cutting times and extended tool life.

[0043] (Test Example 1-2)

A cemented carbide substrate similar to the one used in the Test Example 1-1 was prepared. Thermal CVD was performed on the surface of the obtained substrate to form a coating layer with the film forming conditions
10 (gas composition, pressure, temperature) shown in Table 1. Table 5 shows the composition, film thicknesses, and film thickness of the entire coating layer (total film thickness). In Table 5, the films are indicated sequentially as the first film, the second film, and the like starting from the film closest to the substrate.

[0044] [Table 5]

Test sample No.	First film		Second film		Third film		Fourth film		Fifth film		Sixth film		Total Thickness μm	Cutting time (min)
	Type	Thickness	Type	Thickness	Type	Thickness	Type	Thickness	Type	Thickness	Type	Thickness		
2-1	TiCN	5.0	AlN ^{*1}	7.0									7.0	20
2-2	TiN	0.5	ZrCN	2.0	AlN ^{*1}	0.5							8.0	31
2-3	TiN	1.0	TiCN	4.5	TiC	1.5	TiCNO	1.0	κ -Al ₂ O ₃	3.0	AlCN ^{*1}	5.0	16.0	35
2-4	TiN	0.3	TiCN	6.5	TiBN	0.5	κ -Al ₂ O ₃	1.5	TiN	0.3	AlN ^{*1}	3.0	12.1	27
2-5	TiN	0.5	TiCN	20.0	Al ₂ O ₃ /ZrO ₂	5.0	AlN ^{*1}	2.0					27.5	37
2-6	TiCN	3.0	TiZrCN	5.0	ZrO ₂	2.3	Al ₂ O ₃ /ZrO ₂	2.5	AlON ^{*1}	1.7			14.5	28
2-7	TiCN	3.2	TiN	0.5	HfCN	4.3	AlCN ^{*1}	2.5					10.5	21
2-8	TiN	0.5	TiBN	1.3	α -Al ₂ O ₃	5.0	AlN ^{*1}	0.05					6.85	25
2-9	HfCN	3.5	α -Al ₂ O ₃	1.5	TiCNO	2.3	TiCN	6.5	TiN	0.7	AlCN ^{*1}	0.7	15.2	30
2-10	TiN	5.0	TiZrCN	14.0	AlCN ^{*1}	9.0							28	32
2-11	TiN	0.5	TiCN	4.5	AlCN ^{*1}	0.5	AlN ^{*1}	0.5					6.0	23
2-12	TiN	0.5	TiCNO	2.0	TiCN	6.0	TiBN	0.5	κ -Al ₂ O ₃	1.5	AlCN ^{*1}	0.7	11.2	25
2-13	HfCN	4.0	TiN	1.0									5.0	4
2-14	TiN	0.5	TiCN	5.0	TiCNO	0.5	ZrO ₂	2.0	TiCN	0.1	TiN	2.0	10.1	6
2-15	TiN	0.5	AlON ^{*1}	2.0	α -Al ₂ O ₃	3.0	TiN	1.5					7.0	6
2-16	ZrCN	0.07	AlN ^{*1}	0.02									0.09	8
2-17	TiN	0.5	ZrCN	4.0	AlN ^{*1}	0.02							4.52	11
2-18	TiN	0.5	TiCN	3.0	TiCNO	11.0	α -Al ₂ O ₃	3.5	Al ₂ O ₃ /ZrO ₂	7.0	AlCN ^{*1}	10.0	35.0	7
2-19	TiCN	4.0	TiBN	2.0	ZrO ₂	2.0	AlCN ^{*1}	8.0					16.0	13
2-20	TiN	1.0	ZrCN	4.0	AlON ^{*2}	1.3							6.3	5
2-21	AlN ^{*1}	5.0											5.0	3
2-22	TiN	3.0	AlCN ^{*1}	1.0									4.0	11
2-23	TiZrCN	10.0	AlCN ^{*1}	4.0									14.0	10

[0045] Repeated cutting was performed under the cutting conditions shown below using the surface-coated throw-away inserts with the coating layers shown in Table 5. The cutting time involved in reaching the tool life was measured. The end of tool life was defined to be when flank face wear due to film peeling was at least 0.3 mm. Table 5 shows the results from the test as well.

[0046] Workpiece: 15-second repeated wear resistance test with SCM435

10 round rod

Speed: $V=180$ m/min

Feed: $f=0.2$ mm/rev.

Depth of cut: $d=1.5$ mm

Cutting oil: none

- 5 [0047] As a result, it was found as shown in Table 5 that, compared to the other test samples, the Test Samples 2-1 - 2-12, 2-16 - 2-19, 2-22, and 2-23, which had an aluminum nitride film containing a predetermined amount of chlorine as the outermost layer and films with predetermined compositions as the inner layers, provided superior lubricity and superior wear resistance.
- 10 [0048] Also, the results shown in Table 5 indicate that it would be preferable for the outermost layer to be at least 0.03 microns and for the total film thickness to be at least 0.1 microns and no more than 30 microns. Furthermore, it can be seen that it would be preferable for the outermost layer to have no more than 1/2 the total thickness of the inner layer.
- 15 [0049] The inserts from the test sample 2-1 - 2-23 were all cut and the surface roughness relative to a 5 micron reference length was measured for the area of the outermost layer near the ridge line of the cutting edge that comes into contact with the workpiece. As a result, it was found that R_{max} was no more than 1.3 microns for all inserts except the Test Sample 2-23, while the
- 20 R_{max} of the Test Sample 2-23 was 1.7 microns. For the Test Sample 2-23, a #1500 diamond paste was used to polish the area of the outermost layer near the ridge line of the cutting edge that comes into contact with the workpiece. When the method described above was used to measure surface roughness

after polishing, Rmax was 0.52 microns. When a cutting test was performed under the same cutting conditions using the polished insert, the tool life was 22 min. This is believed to be caused by a reduction in the cutting force resulting from less roughness at the area of the outermost layer near the ridge line of the cutting edge that comes into contact with the workpiece. When the surface roughness of the Test Sample 2-3 was measured as described above, the Rmax was 0.76 microns, but when the cutting edge was polished in the same manner, the tool life after another cutting operation was found to be significantly improved, at 45 min.

[0050] Furthermore, a coating film was formed on the Test Sample 2-22 to make the film hardness of the inner layer higher than that of the outermost layer. Then, the hardnesses of the films forming the coating layers of the Test Samples 2-1 - 2-20, 2-22, and 2-23 were measured. The film hardness of the outermost layer was lower than that of at least one film of the inner layer for all the inserts, with the exception of Test Sample 2-22. With the Test Sample 2-22, the film hardness of the outermost layer was higher than that of the inner layer. Based on this, it is believed that the cutting efficiency of the Test Sample 2-22 was reduced compared to the Test Samples 2-1 - 2-12.

[0051] (Test Example 1-2')

Surface-coated inserts similar to those of the Test Samples 2-1 - 2-23 were prepared and cutting tests were performed under the cutting conditions described below. Crater wear (area: mm²) was then measured for a predetermined cutting length (500 m).

Workpiece: S50C

Speed: $V=250$ m/min

Feed: $f=0.3$ mm/rev.

Depth of cut: $d=1.5$ mm

5 Cutting oil: none

The results showed that the Test Samples 2-1 - 2-12, 2-16 - 2-19, 2-22, and 2-23 had less crater wear compared to the other samples. For example, the results for the Test Samples 2-4, 2-5, and 2-6 were 0.45 mm^2 , 0.39 mm^2 , and 0.44 mm^2 , respectively.

10 [0052] (Test Example 1-3)

Surface-coated inserts were prepared using the substrate described below with a widely known PVD method being used to form a coating layer having a composition similar to that of the Test Samples 2-2, 2-13 from Table 5. For the insert with a coating layer having a composition similar to that of the

15 Test Sample 2-2, the surface-coated insert was formed by adding chlorine to the outermost layer using ion implantation after the coating layer was formed. Cutting tests with cutting conditions similar to those of the Test Example 1-2 were performed using these surface-coated inserts. The test samples formed with the coating layer from the Test Sample 2-2 all had a chlorine content of

20 0.2 atomic percent on the outermost layer.

1. JIS standard: P20 cermet cutting insert (T1200A, Sumitomo Electric Hardmetal Corp. Ltd.)

2. Ceramic cutting insert (W80, Sumitomo Electric Hardmetal Corp. Ltd.)

3. Silicon nitride cutting insert (NS260, Sumitomo Electric Hardmetal Corp. Ltd.)

4. Cubic boron nitride cutting insert (BN250, Sumitomo Electric Hardmetal Corp. Ltd.) The results showed that all the inserts with the coating layer

5 having the composition from the Test Sample 2-2 provided a tool life of at least twice that of conventional inserts with the coating layer having the composition from the Test Sample 2-13.

[0053] (Test Example 1-4)

A powder with 86 percent by mass of WC, 8.0 percent by mass of Co, 2.0
10 percent by mass of TiC, 2.0 percent by mass of NbC, and 2.0 percent by mass of ZrC was prepared. The powder was wet mixed for 72 hours with a ball mill, dried, and then pressed into a green compact with a breaker structure. This green compact was heated for 1 hour in a vacuum atmosphere at 1420 deg C in a sintering furnace, resulting in a sintered body. SiC brush honing and
15 beveling were performed at the ridge line of the cutting edge of the obtained sintered body, resulting in an ISO SNMG120408 throw-away insert formed from WC-based cemented carbide.

[0054] A coating layer was formed on the substrate surface using thermal CVD, a chemical vapor deposition technique. In this test, the following
20 layers were formed, starting from the substrate side: an inner layer formed from TiN(0.5), columnar structure TiCN(6), TiBN(0.5), κ -Al₂O₃(2); and an outermost layer formed from AlN(3). The numbers in parentheses indicate film thickness in microns. Table 6 shows an example of film forming conditions for

each film. Specifically, the composition of the reaction gas (percent by volume), the pressure applied when forming the film (kPa), and the film forming temperature (deg C) are shown. Film thickness was controlled by controlling the film forming time. In this test, the TiCN film was grown so that it has a columnar structure with an aspect ratio of 4.2 and so that the (311) plane has the maximum index of orientation TC. More specifically, the TiN film formation conditions (gas composition, pressure, temperature) were set up so that the reaction gas was CH_3CN , the temperature was 900 deg C, the pressure was 8 kPa, and the surface roughness R_{max} (5 microns reference length) of the TiN film formed below the TiCN film was 0.1 microns. Then, the film forming conditions were varied as shown in Table 6 to form AlN films on the outermost layer with different chlorine content. Table 7 shows chlorine content on the outermost layer. More specifically, test samples were prepared with more than 0 and no more than 0.5 atomic percent chlorine on the outermost layer, more than 0.5 atomic percent chlorine, and no chlorine. The chlorine content was varied by varying the proportion of hydrogen chloride (HCl) in the reaction gas as shown in Table 6. Also, using the amount of hydrogen chloride, the film forming pressure and the film forming temperature were varied as appropriate. Furthermore, the surface roughness at sites on the outermost layer near the ridge line of the cutting edge at areas that come into contact with the workpiece were studied for test samples containing more than 0 and no more than 0.5 atomic percent of chlorine in the outermost layer. Observation of the tool cross-sections showed that the R_{max} for a reference

length of 5 microns was no more than 1.3 microns for all samples. More specifically, the Rmax was 0.6 microns for Test Sample 3-2, for example. The chlorine content was measured using XPS (X-ray Photoelectron Spectroscopy), but composition can also be studied using micro-EDX (Energy Dispersive X-ray Spectroscopy) combined with a transmission electron microscope or using SIMS (Secondary Ion Mass Spectrometry).

[0055] [Table 6]

Coating layer	Reaction gas composition (vol%)	Pressure (kPa)	Temperature (deg C)
AlN *1	AlCl ₃ :1.0 - 5.0%, NH ₃ :0.1 - 5.0%, N ₂ :20 - 50%, HCl:0.01 - 1.0%, H ₂ :rest	4.0 - 80	750 - 980
AlCN *1	AlCl ₃ :1.0 - 5.0%, NH ₃ :0.1 - 5.0%, N ₂ :20 - 50%, CH ₄ :0.5 - 5.0%, HCl:0.01 - 1.0%, H ₂ :rest	4.0 - 80	750 - 980
AlON *1	AlCl ₃ :1.0 - 5.0%, NH ₃ :0.1 - 5.0%, N ₂ :20 - 50%, CO ₂ :0.2 - 3.0%, HCl:0.01 - 1.0%, H ₂ :rest	4.0 - 80	750 - 980
AlN *2	AlCl ₃ :1.5%, NH ₃ :1.0%, N ₂ :40%, H ₂ :rest	5.0	1000
AlN *3	AlCl ₃ :1.5%, NH ₃ :3.0%, N ₂ :40%, HCl:5.0%, H ₂ :rest	13.3	950
AlON *2	AlCl ₃ :1.5%, NH ₃ :6.0%, N ₂ :40%, CO ₂ :1.0%, H ₂ :rest	6.8	1100
TiN	TiCl ₄ :2.0%, N ₂ :25%, H ₂ :rest	13.3	950
TiC	TiCl ₄ :2.0%, CN ₄ :5%, H ₂ :rest	13.3	1050
granularTiCN	TiCl ₄ :4.0%, CH ₄ :4.0%, N ₂ :20%, H ₂ :rest	14	1020
columnarTiCN	TiCl ₄ :3.0%, CH ₃ CN:0.6%, N ₂ :20%, H ₂ :rest	4.0 - 80	800 - 950
ZrCN	ZrCl ₄ :1.0%, CH ₃ CN:0.6%, N ₂ :35%, H ₂ :rest	6.7	890
TiZrCN	TiCl ₄ :1.5%, ZrCl ₄ :1.0%, CH ₃ CN:1.0%, N ₂ :45%, H ₂ :rest	6.7	975
TiCNO	TiCl ₄ :2.0%, CO ₂ :2.5%, N ₂ :8%, H ₂ :rest	6.7	975
TiBN	TiCl ₄ :2.0%, BCl ₃ :5.0%, N ₂ :5.0%, H ₂ :rest	13.3	950
HfCN	HfCl ₄ :1.0%, CH ₃ CN:1.2%, N ₂ :40%, H ₂ :rest	6.7	1025
α Al ₂ O ₃	AlCl ₃ :2.0%, H ₂ S:0.3%, CO ₂ :5.0%, H ₂ :rest	6.7	1050
κ Al ₂ O ₃	AlCl ₃ :2.0%, CO ₂ :5.0%, CO:0.5%, H ₂ :rest	6.7	1000
ZrO ₂	ZrCl ₄ :2.0%, CO ₂ :7.0%, H ₂ :rest	6.7	1050
Al ₂ O ₃ /ZrO ₂	AlCl ₃ :1.5%, ZrCl ₄ :0.3%, CO ₂ :9.0%, H ₂ :rest	13.3	1070

*1: Chlorine content is more than 0 and no more than 0.5 atomic percent

*2: No chlorine

*3: Chlorine content is more than 0.5 atomic percent

[0056] [Table 7]

Test sample No.	Outermost layer	Chlorine content (atomic percent)
3-1	AlN *1	0.02
3-2	AlN *1	0.15
3-3	AlN *1	0.49
3-4	AlN *2	0
3-5	AlN *3	0.90

[0057] Using the surface-coated throw-away inserts with the outermost layers as shown in Table 7, continuous cutting operations were performed using the cutting conditions shown in Table 8. The cutting time involved in reaching the tool life was measured. In a peeling resistance test, cutting operations were repeated, with the end of tool life defined to be when flank face wear due to film peeling was at least 0.3 mm. In a wear resistance test, tool life was defined to be when the flank face wear was at least 0.3 mm. The results of the tests are shown in Table 9.

[0058] [Table 8]

	Peeling resistance test	Fracture resistance test
Workpiece	S15C rod 3 sec repetition test	S45C rod
Speed	V=300m/min	V=260m/min
Feed	f=0.3mm/rev.	f=0.2mm/rev.
Cutting depth	d=1.0mm	d=1.5mm
Cutting oil	None	None

[0059] [Table 9]

Test Sample No.	Cutting time (min)	
	Peeling resistance test	Wear resistance test
3-1	42	24
3-2	60	31
3-3	51	21
3-4	12	6
3-5	10	5

[0060] Based on the results, in the Test Samples 3-1 through 3-3, which have aluminum nitride layers with more than 0 and not more than 0.5 atomic percent of chlorine on the outermost layer as shown in Table 9, superior lubricity and improved welding resistance was observed even in dry cutting. This improved welding resistance and provided superior peeling resistance by reducing cutting force. Also, since a predetermined TiCN film is used in the inner layer, the Test Samples 3-1 - 3-3 also provide superior wear resistance. Furthermore, chipping did not take place with these Test Samples 3-1 - 3-3. Thus superior chipping resistance and fracturing resistance are provided. Based on these factors, it can be seen that the Test Samples 3-1 - 3-3 provide longer cutting times and extended tool life.

[0061] (Test Example 1-5)

A cemented carbide substrate similar to the one used in the Test Example 1-4 was prepared. Thermal CVD was performed on the surface of the obtained substrate to form a coating layer with the film forming conditions (gas composition, pressure, temperature) shown in Table 6. In this test, the following layers were formed, starting from the substrate side: TiN(0.5), columnar structure TiCN(4) or granular structure TiCN(4), TiBN(0.5), Al₂O₃-

ZrO₂(2); and an outermost layer formed from AlN^{*1}(3) (Test Sample 3-3 from Table 7). The numbers in parentheses indicate film thickness in microns. Film thickness was controlled by controlling the film forming time. In this test, the aspect ratio and the face with the maximum index of orientation of the columnar structure TiCN film are varied, as shown in Table 6, by varying the film forming pressure and temperature as well as by varying the surface roughness and gas conditions for the TiN film formed below the TiCN film. More specifically, the aspect ratio of the TiCN film was set to at least 3 by using CH₃CN as the reaction gas, with the gas temperature set to 920 deg C and the pressure set to 6 kPa and the CH₃CN reaction gas being introduced gradually. Also, if the TiCN film maximum index of orientation TC is to be (422), for example, the surface roughness Rmax (5 microns reference length) of the substrate is set to 0.09 microns and the TiCN film is formed while adjusting the aspect ratio outward from the substrate (away from the substrate). Furthermore, for all the test samples, the surface of the outermost layer was polished after forming the outermost layer so that the section of the outermost layer around the ridge line of the cutting edge that comes into contact with the workpiece had a surface roughness Rmax of 0.4 microns for 5 microns reference length when measured by observing tool cross-sections. Table 10 shows TiCN film composition, aspect ratio, and the face with the maximum index of orientation TC.

[0062] [Table 10]

Test sample No.	Inner layer TiCN film			Cutting time (min) Wear resistance test
	Structure	Aspect ratio	Face with maximum TC	
4-1	Columnar	5.2	311	21
4-2	Columnar	6.6	422	25
4-3	Columnar	3.1	220	19
4-4	Columnar	2.3	220	4
4-5	Columnar	3.5	420	5
4-6	Granular	-	311	1

[0063] Using the surface-coated throw-away inserts with TiCN film inner layers as shown in Table 10, continuous cutting operations were performed using the cutting conditions described below. The cutting time involved in reaching the tool life was measured. The end of tool life was defined to be when flank face wear due to film peeling was at least 0.3 mm. Table 10 shows the results from the test as well.

[0064] Workpiece: wear resistance test with stainless steel rod

10 Speed: $V=200$ m/min

Feed: $f=0.2$ mm/rev.

Depth of cut: $d=1.5$ mm

Cutting oil: none

[0065] The results show that with a TiCN film as in Table 10, a columnar structure provides superior wear resistance. More specifically, with the Test Samples 4-1 - 4-3, which are formed with columnar structure TiCN film at the inner layer with an aspect ratio of at least 3 and a maximum index of orientation of TC(311), TC(220), or TC(422), wear resistance is especially superior and tool life is longer, even when dry cutting. The longer tool life is

believed to be because of the superior lubricity of the outermost layer and the inner layer and the use of a predetermined TiCN film with superior wear resistance.

[0066] (Test Example 1-6)

5 A cemented carbide substrate similar to the one used in the Test Example 1-4 was prepared. Thermal CVD was performed on the surface of the obtained substrate to form a coating layer with the film forming conditions (gas composition, pressure, temperature) shown in Table 6. In this test, the film forming conditions were controlled so that columnar structure TiCN films
10 had an aspect ratio of at least 3 and the maximum index of orientation was TC(311), TC(220), or TC(422). Table 11 shows the composition, film thicknesses, and the film thickness of the entire coating layer (total film thickness). In Table 11, the films are indicated sequentially as the first film, the second film, and the like starting from the film closest to the substrate.

[0067] [Table 11]

Test Sample No.	First film		Second film		Third film		Fourth film		Fifth film		Sixth film		Total Thickness μm	Cutting time min
	Type	Thickness	Type	Thickness	Type	Thickness	Type	Thickness	Type	Thickness	Type	Thickness		
5-1	columnar TiCN	5.0	AIN*1	2.0									7.0	21
5-2	columnar TiCN	0.5	ZrCN	7.0	AIN*1	0.5							8.0	31
5-3	TiN	1.0	columnar TiCN	4.5	TiC	1.5	TiCNO	1.0	κ -Al ₂ O ₃	3.0	AlCN*1	5.0	16.0	37
5-4	TiN	0.3	columnar TiCN	6.5	TiBN	0.5	κ -Al ₂ O ₃	1.5	TiN	0.3	AIN*1	3.0	12.1	27
5-5	TiN	0.5	columnar TiCN	20.0	Al ₂ O ₃ /ZrO ₂	5.0	AIN*1	2.0					27.5	35
5-6	columnar TiCN	3.0	TiZrCN	5.0	ZrO ₂	2.3	Al ₂ O ₃ /ZrO ₂	2.5	AlON*1	1.7			14.5	26
5-7	columnar TiCN	3.2	TiN	0.5	HfCN	4.3	AlCN*1	2.5					10.5	23
5-8	columnar TiCN	0.5	TiBN	1.3	α -Al ₂ O ₃	5.0	AIN*1	0.05					6.85	26
5-9	HfCN	3.5	α -Al ₂ O ₃	1.5	TiCNO	2.3	columnar TiCN	6.5	TiN	0.7	AlCN*1	0.7	15.2	32
5-10	columnar TiCN	5.0	TiZrCN	14.0	AlCN*1	9.0							28	32
5-11	TiN	0.5	columnar TiCN	4.5	AlCN*1	0.5	AIN*1	0.5					6.0	25
5-12	TiN	0.5	TiCNO	2.0	columnar TiCN	6.0	TiBN	0.5	κ -Al ₂ O ₃	1.5	AlCN*1	0.7	11.2	23
5-13	columnar TiCN	2.0	HfCN	2.0	TiN	1.0							5.0	6
5-14	TiN	0.5	columnar TiCN	5.0	TiCNO	0.5	ZrO ₂	2.0	columnar TiCN	0.1	TiN	2.0	10.1	7
5-15	columnar TiCN	0.5	AlON*1	2.0	α -Al ₂ O ₃	3.0	TiN	1.5					7.0	5
5-16	columnar TiCN	0.07	AIN*1	0.02									0.09	8
5-17	columnar TiCN	0.5	ZrCN	4.0	AIN*1	0.02							4.52	11
5-18	TiN	0.5	columnar TiCN	3.0	TiCNO	11.0	α -Al ₂ O ₃	3.5	Al ₂ O ₃ /ZrO ₂	7.0	AlCN*1	10.0	35.0	8
5-19	columnar TiCN	4.0	TiBN	2.0	ZrO ₂	2.0	AlCN*1	8.0					16.0	14
5-20	TiN	0.2	columnar TiCN	0.8	ZrCN	4.0	AlON*2	1.3					6.3	7
5-21	columnar TiCN	10.0	AlCN*1	4.0									14.0	10

[0068] Using the surface-coated throw-away inserts with TiCN film inner layers as shown in Table 11, continuous cutting operations were

performed using the cutting conditions described below. The cutting time involved in reaching the tool life was measured. The end of tool life was defined to be when flank face wear due to film peeling was at least 0.3 mm. Table 11 shows the results from the test as well.

- 5 [0069] Workpiece: 15-second repetitive wear resistance test with SCM435 rod

Speed: $V=180$ m/min

Feed: $f=0.2$ mm/rev.

Depth of cut: $d=1.5$ mm Cutting oil: none

- 10 [0070] As a result, it was found as shown in Table 11 that, compared to the other test samples, the Test Samples 5-1 - 5-12, 5-16 - 5-19, 5-21, which had an aluminum nitride film containing a predetermined amount of chlorine as the outermost layer and a columnar structure TiCN film inner layer with an aspect ratio of at least 3 and a maximum index of orientation of TC(311),
15 TC(220), or TC(422), provided superior lubricity and superior wear resistance.

- [0071] Also, the results shown in Table 11 indicate that it would be preferable for the outermost layer to be at least 0.03 microns and for the total film thickness to be at least 0.1 microns and no more than 30 microns. Furthermore, it can be seen that it would be preferable for the outermost layer
20 to have no more than 1/2 the total thickness of the inner layer.

[0072] The inserts from the test sample 5-1 - 5-21 were all cut and the surface roughness relative to a 5 micron reference length was measured for the area of the outermost layer near the ridge line of the cutting edge that comes

into contact with the workpiece. As a result, it was found that Rmax was no more than 1.3 microns for all inserts except the Test Sample 5-21, while the Rmax of the Test Sample 5-21 was 1.7 microns. For the Test Sample 5-21, a #1500 diamond paste was used to polish the area of the outermost layer near the ridge line of the cutting edge that comes into contact with the workpiece. When the method described above was used to measure surface roughness after polishing, Rmax was 0.52 microns. When a cutting test was performed under the same cutting conditions using the polished insert, the tool life was 24 min. This is believed to be caused by a reduction in the cutting force resulting from less roughness at the area of the outermost layer near the ridge line of the cutting edge that comes into contact with the workpiece. When the surface roughness of the Test Sample 5-3 was measured as described above, the Rmax was 0.76 microns, but when the cutting edge was polished in the same manner, the tool life after another cutting operation was found to be significantly improved, at 48 min.

[0073] (Test Example 1-6')

Surface-coated inserts similar to those of the Test Samples 5-1 - 5-21 were prepared and cutting tests were performed under the cutting conditions described below. Crater wear (area: mm^2) was then measured for a predetermined cutting length (500 m).

Workpiece: S50C

Speed: $V=250 \text{ m/min}$

Feed: $f=0.3 \text{ mm/rev.}$

Depth of cut: $d=1.5$ mm

Cutting oil: none The results showed that the Test Samples 5-1 - 5-12, 5-16 - 5-19, and 5-21 had less crater wear compared to the other samples. For example, the results for the Test Samples 5-4, 5-5, and 5-6 were 0.3 mm^2 , 0.27
 5 mm^2 , and 0.29 mm^2 , respectively.

[0074] (Test Example 1-7)

Using the substrate described below, a coating film having a composition similar to that of the Test Sample 5-2 from Table 11 was formed using a widely known PVD method. Surface-coated inserts were formed by
 10 adding chlorine to the outermost layer using ion implantation after the coating layer was formed. Cutting tests were performed under cutting conditions similar to those of the Test Example 1-6.

The chlorine content of the outermost layer was 0.18 atomic percent in all cases.

- 15 1. JIS standard: P20 cermet cutting insert (T1200A, Sumitomo Electric Hardmetal Corp. Ltd.)
2. Ceramic cutting insert (W80, Sumitomo Electric Hardmetal Corp. Ltd.)
3. Silicon nitride cutting insert (NS260, Sumitomo Electric Hardmetal Corp. Ltd.)
- 20 4. Cubic boron nitride cutting insert (BN250, Sumitomo Electric Hardmetal Corp. Ltd.) The results indicated that all the coated inserts provided superior lubricity and wear resistance.

Based on this, it can be seen that tool life can be improved in the same

manner as when a cemented carbide is used as described above.

[Second Example]

[0075] The present invention will be described in more detail, using end mills as an example.

5 (Test Example 2-1)

Two-edge square end mill substrates (solid end mills) formed from cemented carbide corresponding to JIS Z20 (10 mm diameter) were prepared. Thermal CVD, which is a chemical vapor deposition technique, was performed to form a coating layer on the substrate at the surface of the areas (body) associated with cutting. In this test, the following layers were formed, starting from the substrate side: an inner layer formed from TiN(0.5), TiCN(4), TiBN(0.5), κ -Al₂O₃(1); and an outermost layer formed from AlN (1.5). The numbers in parentheses indicate film thickness in microns. Table 12 shows an example of film forming conditions for each film. Specifically, the composition of the reaction gas (percent by volume), the pressure applied when forming the film (kPa), and the film forming temperature (deg C) are shown. Film thickness was controlled by controlling the film forming time. Test samples in which the AlN film at the outermost layer have different chlorine contents were prepared by varying the film forming conditions as shown in Table 12. Table 13 shows chlorine content at the outermost layer. Specifically, samples with more than 0 and no more than 0.5 atomic percent of chlorine, samples with more than 0.5 atomic percent of chlorine, and samples with no chlorine were prepared. Chlorine content was varied as shown in Table 12 by varying

the proportion of hydrogen chloride (HCl) in the reaction gas. Also, using the amount of hydrogen chloride, the film forming pressure and the film forming temperature were varied as appropriate. Furthermore, the surface roughness at sites on the outermost layer near the ridge line of the cutting edge at areas that come into contact with the workpiece were studied for test samples containing more than 0 and no more than 0.5 atomic percent of chlorine in the outermost layer. Observation of the tool cross-sections showed that the Rmax for a reference length of 5 microns was no more than 1.3 microns for all samples. More specifically, the Rmax was 0.6 microns for Test Sample 6-2, for example. The chlorine content was measured using XPS (X-ray Photoelectron Spectroscopy), but composition can also be studied using micro-EDX (Energy Dispersive X-ray Spectroscopy) combined with a transmission electron microscope or using SIMS (Secondary Ion Mass Spectrometry). Also, the Knoop hardness for each of the layers in the test samples was studied, and it was found that in all cases the outermost AlN film was harder than the inner TiCN film layer.

[0076] [Table 12]

Coating layer	Reaction gas composition (vol%)	Pressure (kPa)	Temperature (deg C)
AlN *1	AlCl ₃ :1.0 - 5.0%, NH ₃ :0.1 - 5.0%, N ₂ :20 - 50%, HCl:0.01 - 1.0%, H ₂ :rest	4.0 - 80	750 - 980
AlCN *1	AlCl ₃ :1.0 - 5.0%, NH ₃ :0.1 - 5.0%, N ₂ :20 - 50%, CH ₄ :0.5 - 5.0%, HCl:0.01 - 1.0%, H ₂ :rest	4.0 - 80	750 - 980
AlON *1	AlCl ₃ :1.0 - 5.0%, NH ₃ :0.1 - 5.0%, N ₂ :20 - 50%, CO ₂ :0.2 - 3.0%, HCl:0.01 - 1.0%, H ₂ :rest	4.0 - 80	750 - 980
AlN *2	AlCl ₃ :1.5%, NH ₃ :1.0%, N ₂ :40%, H ₂ :rest	5.0	1000
AlN *3	AlCl ₃ :1.5%, NH ₃ :3.0%, N ₂ :40%, HCl:5.0%, H ₂ :rest	13.3	950
AlON *2	AlCl ₃ :1.5%, NH ₃ :6.0%, N ₂ :40%, CO ₂ :1.0%, H ₂ :rest	6.8	1100
TiN	TiCl ₄ :2.0%, N ₂ :25%, H ₂ :rest	13.3	950
TiC	TiCl ₄ :2.0%, CN ₄ :5%, H ₂ :rest	13.3	1050
TiCN	TiCl ₄ :2.0%, CH ₃ CN:0.6%, N ₂ :20%, H ₂ :rest	6.7 - 80	800 - 950
ZrCN	ZrCl ₄ :1.0%, CH ₃ CN:0.6%, N ₂ :35%, H ₂ :rest	6.7	890
TiZrCN	TiCl ₄ :1.5%, ZrCl ₄ :1.0%, CH ₃ CN:1.0%, N ₂ :45%, H ₂ :rest	6.7	975
TiCNO	TiCl ₄ :2.0%, CO ₂ :2.5%, N ₂ :8%, H ₂ :rest	6.7	975
TiBN	TiCl ₄ :2.0%, BCl ₃ :5.0%, N ₂ :5.0%, H ₂ :rest	13.3	950
HfCN	HfCl ₄ :1.0%, CH ₃ CN:1.2%, N ₂ :40%, H ₂ :rest	6.7	1025
α Al ₂ O ₃	AlCl ₃ :2.0%, H ₂ S:0.3%, CO ₂ :5.0%, H ₂ :rest	6.7	1050
κ Al ₂ O ₃	AlCl ₃ :2.0%, CO ₂ :5.0%, CO:0.5%, H ₂ :rest	6.7	1000
ZrO ₂	ZrCl ₄ :2.0%, CO ₂ :7.0%, H ₂ :rest	6.7	1050
Al ₂ O ₃ -ZrO ₂	AlCl ₃ :1.5%, ZrCl ₄ :0.3%, CO ₂ :9.0%, H ₂ :rest	13.3	1070

*1: Chlorine content is more than 0 and no more than 0.5 atomic percent

*2: No chlorine

*3: Chlorine content is more than 0.5 atomic percent

5

[0077] [Table 13]

Test sample No.	Outermost layer	Chlorine content (atomic %)
6-1	AlN *1	0.03
6-2	AlN *1	0.18
6-3	AlN *1	0.48
6-4	AlN *2	0
6-5	AlN *3	0.98

[0078] Using the cutting conditions shown in Table 14, the cutting efficiency of surface-coated end mills with outermost layers as shown in Table 13 was observed. For the cutting conditions 1, the wear for a fixed cutting length (150 mm) was measured. In this test, the flank face wear (microns) on the peripheral cutting edge was measured. For the cutting conditions 2, a fixed boring operation (10 mm diameter) was performed. The torque applied during boring was measured and the state after changing to a fixed slot milling operation (50 mm) after the boring operation was observed. The results of the tests are shown in Table 15.

10 [0079] [Table 14]

Cutting conditions 1	Cutting conditions 2
Side milling	10mm boring, then 50mm fluting
Workpiece: S50C	Workpiece: SKD11
Speed: V=300m/min	Speed: V=80m/min
Feed per cutting edge: $f_t=0.1\text{mm}$	Feed: Boring 0.07mm/rev., Fluting 0.15mm/t (per cutting edge)
Axial cutting depth: $A_d=8\text{mm}$	Cutting oil: None
Radial cutting depth: $R_d=0.5\text{mm}$	
Cutting oil: None	Cutting oil: None
Cutting distance: 150m	

[0080] [Table 15]

Test sample No.	Cutting conditions 1	Cutting conditions 2
	Flank face wear (peripheral cutting edge, microns)	Maximum torque (N · cm)
6-1	55	610
6-2	31	410
6-3	42	550
6-4	92	1050 (breakage during fluting)
6-5	115 (chipping)	1120 (breakage during fluting)

[0081] Based on the results, in the Test Samples 6-1 through 6-3, which have aluminum nitride layers with more than 0 and not more than 0.5 atomic percent of chlorine on the outermost layer as shown in Table 15, wear was reduced and superior lubricity and improved fracturing resistance due to reduced cutting force was observed even in dry cutting. Because the Test Samples 6-1 - 6-3 were formed with a coating layer having superior lubricity, chip ejection qualities were good. As a result, torque increases were limited and breaking resistance was improved, allowing problem-free cutting. With the Test Samples 6-4, 6-5, torque increased and breakage occurred when switching to slot milling. Furthermore, these Test Samples 6-1 - 6-3 provided superior welding resistance and peeling of the coating layer and the like did not take place. Based on these factors, it could be seen that the Test Samples 6-1 - 6-3 were able to extend tool life.

[0082] (Test Example 2-2)

15 Substrates similar to those from the cemented carbide end mill substrates used in the Test Example 2-1 were prepared. Thermal CVD was performed on the area associated with cutting, and coating layers were formed under the film forming conditions (gas composition, pressure, temperature) shown in Table 12. Table 16 shows the composition, film thicknesses, and the film thickness of the entire coating layer (total film thickness). In Table 16, the films are indicated sequentially as the first film, the second film, and the like starting from the film closest to the substrate.

[0083] [Table 16]

Test Sample No.	First film		Second film		Third film		Fourth film		Fifth film		Sixth film		Total thickness μm	Flank face wear μm
	Type	Thickness	Type	Thickness	Type	Thickness	Type	Thickness	Type	Thickness	Type	Thickness		
7-1	TiCN	3.0	AlN ¹	1.0									4.0	62
7-2	TiN	0.5	ZrCN	7.0	AlN ¹	0.5							8.0	35
7-3	TiN	1.0	TiCN	4.5	TiC	1.5	TiCN	1.0	$\kappa\text{-Al}_2\text{O}_3$	3.0	AlCN ¹	5.0	16.0	33
7-4	TiN	0.3	TiCN	6.5	TiBN	0.5	$\kappa\text{-Al}_2\text{O}_3$	1.5	TiN	0.3	AlN ¹	3.0	12.1	53
7-5	TiN	0.5	TiCN	14.0	Al ₂ O ₃ /ZrO ₂	5.0	AlN ¹	2.0					21.5	31
7-6	TiCN	3.0	TiZrCN	5.0	ZrO ₂	2.3	Al ₂ O ₃ /ZrO ₂	2.5	AlON ¹	1.7			14.5	44
7-7	TiCN	3.2	TiN	0.5	HfCN	4.3	AlCN ¹	2.5					10.5	60
7-8	TiN	0.5	TiBN	1.3	$\alpha\text{-Al}_2\text{O}_3$	5.0	AlN ¹	0.05					6.85	52
7-9	HfCN	3.5	$\alpha\text{-Al}_2\text{O}_3$	1.5	TiCN	2.3	TiCN	6.5	TiN	0.7	AlCN ¹	0.7	15.2	41
7-10	TiN	2.0	TiZrCN	14.0	AlCN ¹	7.0							23	35
7-11	TiN	0.5	TiCN	4.5	AlCN ¹	0.5	AlN ¹	0.5					6.0	56
7-12	TiN	0.5	TiCN	2.0	TiCN	6.0	TiBN	0.5	$\kappa\text{-Al}_2\text{O}_3$	1.5	AlCN ¹	0.7	11.2	54
7-13	HfCN	4.0	TiN	1.0									5.0	135
7-14	TiN	0.5	TiCN	5.0	TiCN	0.5	ZrO ₂	2.0	TiCN	0.1	TiN	2.0	10.1	180
7-15	TiN	0.5	AlON ¹	2.0	$\alpha\text{-Al}_2\text{O}_3$	3.0	TiN	1.5					7.0	128
7-16	ZrCN	0.07	AlN ¹	0.02									0.09	82
7-17	TiN	0.5	ZrCN	4.0	AlN ¹	0.02							4.52	95
7-18	TiN	0.5	TiCN	3.0	TiCN	9.0	$\alpha\text{-Al}_2\text{O}_3$	3.5	Al ₂ O ₃ /ZrO ₂	5.0	AlCN ¹	8.0	29.0	98
7-19	TiCN	4.0	TiBN	2.0	ZrO ₂	2.0	AlCN ¹	7.0					15.0	92
7-20	TiN	1.0	ZrCN	4.0	AlON ²	1.3							6.3	210
7-21	AlN ¹	5.0											5.0	165
7-22	TiN	3.0	AlCN ¹	1.0									4.0	88
7-23	TiZrCN	10.0	AlCN ¹	4.0									14.0	93

[0084] The surface-coated end mills with the coatings shown in Table 16 were used to perform side milling under the conditions described below, and wear for a fixed cutting length (100 m) was measured. In this test, the flank face wear (microns) on the peripheral cutting edge was measured. Table 16 shows the results from the test as well.

[0085] End mill side milling

Workpiece: SUS304

Speed: V=130 m/min

Feed per cutting edge: $f_t=0.03$ mm

Axial cutting depth: $A_d=8$ mm

Radial cutting depth: $R_d=0.16$ mm

Cutting oil: none Cutting length: 100 m

5 [0086] As a result, it was found as shown in Table 16 that, compared to the other test samples, the Test Samples 7-1 - 7-12, 7-16 - 7-19, 7-22, 7-23, which had an aluminum nitride film containing a predetermined amount of chlorine as the outermost layer and an inner layer with films having a predetermined composition, provided superior lubricity and superior wear
10 resistance.

[0087] Also, the results shown in Table 16 indicate that it would be preferable for the outermost layer to be at least 0.03 microns and for the total film thickness to be at least 0.1 microns and no more than 24 microns. Furthermore, it can be seen that it would be preferable for the outermost layer
15 to have no more than 1/2 the total thickness of the inner layer.

[0088] The end mills from the test sample 7-1 - 7-23 were all cut and the surface roughness relative to a 5 micron reference length was measured for the area of the outermost layer near the ridge line of the cutting edge of the peripheral cutting edge that comes into contact with the workpiece. As a result,
20 it was found that R_{max} was no more than 1.3 microns for all inserts except the Test Sample 7-22, while the R_{max} of the Test Sample 7-22 was 1.7 microns. For the Test Sample 7-22, a #1500 diamond paste was used to polish the area of the outermost layer of the peripheral cutting edge near the ridge line of the

cutting edge that comes into contact with the workpiece. When the method described above was used to measure surface roughness after polishing, R_{max} was 0.52 microns. When side milling was performed under the same cutting conditions using the polished end mill, the flank face wear was 65 microns.

- 5 This is believed to be caused by a reduction in the cutting force resulting from less roughness at the area of the outermost layer near the ridge line of the cutting edge that comes into contact with the workpiece. When the surface roughness of the Test Sample 7-1 was measured as described above, the R_{max} was 0.9 microns, but when the cutting edge was polished in the same manner,
- 10 the flank face wear after another cutting operation was found to be significantly improved, at 35 microns.

- [0089] Furthermore, a coating film was formed on the Test Sample 7-23 to make the film hardness of the inner layer higher than that of the outermost layer. Then, the hardnesses of the films forming the coating layers of the Test
- 15 Samples 7-1 - 7-20, 7-22, and 7-23 were measured. The film hardness of the outermost layer was lower than that of at least one film of the inner layer for all the end mills, with the exception of Test Sample 7-23. With the Test Sample 7-23, the film hardness of the outermost layer was higher than that of the inner layer. As a result, it is believed that the cutting efficiency of the Test
- 20 Sample 7-23 was reduced.

[0090] (Test Example 2-2')

Surface-coated end mills similar to those of the Test Samples 7-1 - 7-23 were prepared and cutting tests were performed under the cutting conditions

described below. Crater wear (width) was then measured for a predetermined cutting length (50 m). Measurements were made of crater wear widths on the peripheral cutting edge. Because end mills have a three-dimensional shape, this width was measured obliquely. More specifically, crater wear width was measured by observing from a fixed angle.

Results were evaluated based on these measurements by comparing the different test samples.

Workpiece: S50C

Speed: $V=100$ m/min

10 Feed: $f=0.05$ mm/t

Cutting depth: $A_d=10$ mm $R_d=0.6$ mm

Cutting oil: none (air blower) The results indicated that crater wear was lower for the Test Samples 7-1 - 7-12, 7-16 - 7-19, 7-22, 7-23 compared to the other test samples. For example, if the wear width of the Test Sample 7-14 is defined as 1, the Test Samples 7-3, 7-6 had the values 0.44 and 0.52 respectively.

[0091] (Test Example 2-3)

Surface-coated end mills were prepared using the substrate described below with a widely known PVD method being used to form a coating layer having a composition similar to that of the Test Samples 7-2, 7-13 from Table 16. For the end mill with a coating layer having a composition similar to that of the Test Sample 7-2, the surface-coated end mill was formed by adding chlorine to the outermost layer using ion implantation after the coating layer

was formed. Then, side milling was performed using the same cutting conditions as the Test Example 2-2. The coating layers were all formed at areas associated with cutting.

The test samples with the coating layer from the Test Sample 7-2 all had a chlorine content of 0.2 atomic percent on the outermost layer.

1 Brazed end mill substrate formed from cemented carbide corresponding to JIS Z20 (cutting section is cemented carbide)

2 Two-edge square end mill substrate formed from JIS-standard P20 cermet (10 mm diameter)

10 3 Brazed ball mill formed from cubic boron nitride (Sumitomo Electric Hardmetal Corp. Ltd., BN300) (cutting section is cubic boron nitride) The results indicated that all the surface-coated end mills formed with the coating layer from the Test Sample 7-2 provided superior lubricity and wear resistance. It was found that the tool life was at least twice that of end mills formed with the conventional coating layer from the Test Sample 7-13.

[0092] (Test Example 2-4)

Two-edge square end mill substrates (solid end mills) formed from cemented carbide corresponding to JIS Z20 (10 mm diameter) were prepared. Thermal CVD, which is a chemical vapor deposition technique, was performed to form a coating layer on the substrate at the surface of the areas (body) associated with cutting. In this test, the following layers were formed, starting from the substrate side: TiN(0.5), columnar structure TiCN(4), TiBN(0.5), κ - Al_2O_3 (1); and an outermost layer formed from AlN (1.5). The numbers in

parentheses indicate film thickness in microns. Table 17 shows an example of film forming conditions for each film. Specifically, the composition of the reaction gas (percent by volume), the pressure applied when forming the film (kPa), and the film forming temperature (deg C) are shown. Film thickness

5 was controlled by controlling the film forming time. In this test, the TiCN film has a columnar structure with an aspect ratio of 4.1 and the index of orientation TC is highest at the (311) face. More specifically, the TiN film formation conditions (gas composition, pressure, temperature) were set up so that the reaction gas was CH_3CN , the temperature was 900 deg C, the

10 pressure was 8 kPa, and the surface roughness R_{max} (5 microns reference length) of the TiN film formed below the TiCN film was 0.1 microns. Test samples in which the AlN film at the outermost layer have different chlorine contents were prepared by varying the film forming conditions as shown in Table 17. Table 18 shows chlorine content at the outermost layer. Specifically,

15 samples with more than 0 and no more than 0.5 atomic percent of chlorine, samples with more than 0.5 atomic percent of chlorine, and samples with no chlorine were prepared. Chlorine content was varied as shown in Table 17 by varying the proportion of hydrogen chloride (HCl) in the reaction gas. Also, using the amount of hydrogen chloride, the film forming pressure and the film

20 forming temperature were varied as appropriate. Furthermore, the surface roughness at sites on the outermost layer near the ridge line of the cutting edge at areas that come into contact with the workpiece were studied for test samples containing more than 0 and no more than 0.5 atomic percent of

chlorine in the outermost layer. Observation of the tool cross-sections showed that the Rmax for a reference length of 5 microns was no more than 1.3 microns for all samples. More specifically, the Rmax was 0.6 microns for Test Sample 8-2, for example. The chlorine content was measured using XPS (X-ray
5 Photoelectron Spectroscopy), but composition can also be studied using micro-EDX (Energy Dispersive X-ray Spectroscopy) combined with a transmission electron microscope or using SIMS (Secondary Ion Mass Spectrometry).

[0093] [Table 17]

Coating layer	Reaction gas composition (vol %)	Pressure (kPa)	Temperature (deg C)
AlN *1	AlCl ₃ :1.0 - 5.0%, NH ₃ :0.1 - 5.0%, N ₂ :20 - 50%, HCl:0.01 - 1.0%, H ₂ :rest	4.0 - 80	750 - 980
AlCN *1	AlCl ₃ :1.0 - 5.0%, NH ₃ :0.1 - 5.0%, N ₂ :20 - 50%, CH ₄ :0.5 - 5.0%, HCl:0.01 - 1.0%, H ₂ :rest	4.0 - 80	750 - 980
AlON *1	AlCl ₃ :1.0 - 5.0%, NH ₃ :0.1 - 5.0%, N ₂ :20 - 50%, CO ₂ :0.2 - 3.0%, HCl:0.01 - 1.0%, H ₂ :rest	4.0 - 80	750 - 980
AlN *2	AlCl ₃ :1.5%, NH ₃ :1.0%, N ₂ :40%, H ₂ :rest	5.0	1000
AlN *3	AlCl ₃ :1.5%, NH ₃ :3.0%, N ₂ :40%, HCl:5.0%, H ₂ :rest	13.3	950
AlON *2	AlCl ₃ :1.5%, NH ₃ :6.0%, N ₂ :40%, CO ₂ :1.0%, H ₂ :rest	6.8	1100
TiN	TiCl ₄ :2.0%, N ₂ :25%, H ₂ :rest	13.3	950
TiC	TiCl ₄ :2.0%, CN ₄ :5%, H ₂ :rest	13.3	1050
Granular TiCN	TiCl ₄ :4.0%, CH ₄ :4.0%, N ₂ :20%, H ₂ :rest	14	1020
Columnar TiCN	TiCl ₄ :3.0%, CH ₃ CN:0.6%, N ₂ :20%, H ₂ :rest	4.0 - 80	800 - 950
ZrCN	ZrCl ₄ :1.0%, CH ₃ CN:0.6%, N ₂ :35%, H ₂ :rest	6.7	890
TiZrCN	TiCl ₄ :1.5%, ZrCl ₄ :1.0%, CH ₃ CN:1.0%, N ₂ :45%, H ₂ :rest	6.7	975
TiCNO	TiCl ₄ :2.0%, CO ₂ :2.5%, N ₂ :8%, H ₂ :rest	6.7	975
TiBN	TiCl ₄ :2.0%, BCl ₃ :5.0%, N ₂ :5.0%, H ₂ :rest	13.3	950
HfCN	HfCl ₄ :1.0%, CH ₃ CN:1.2%, N ₂ :40%, H ₂ :rest	6.7	1025
α Al ₂ O ₃	AlCl ₃ :2.0%, H ₂ S:0.3%, CO ₂ :5.0%, H ₂ :rest	6.7	1050
κ Al ₂ O ₃	AlCl ₃ :2.0%, CO ₂ :5.0%, CO:0.5%, H ₂ :rest	6.7	1000
ZrO ₂	ZrCl ₄ :2.0%, CO ₂ :7.0%, H ₂ :rest	6.7	1050
Al ₂ O ₃ -ZrO ₂	AlCl ₃ :1.5%, ZrCl ₄ :0.3%, CO ₂ :9.0%, H ₂ :rest	13.3	1070

*1: Chlorine content is more than 0 and no more than 0.5 atomic percent

*2: No chlorine

*3: Chlorine content is more than 0.5 atomic percent

[0094] [Table 18]

Test sample No.	Outermost layer	Chlorine content (atomic %)
8-1	AlN *1	0.03
8-2	AlN *1	0.18
8-3	AlN *1	0.48
8-4	AlN *2	0
8-5	AlN *3	0.98

[0095] Using the cutting conditions shown in Table 19, the cutting efficiency of surface-coated end mills with outermost layers as shown in Table 18 was observed. For the cutting conditions I, the wear for a fixed cutting length (150 m) was measured. In this test, the flank face wear (microns) on the peripheral cutting edge was measured. For the cutting conditions II, a fixed boring operation (10 mm diameter) was performed. The torque applied during boring was measured and the state after changing to a fixed slot milling operation (50 mm) after the boring operation was observed. The results of the tests are shown in Table 20.

[0096] [Table 19]

Cutting conditions I	Cutting conditions II
Side milling	10 mm boring, 50 mm fluting
Workpiece:S50C	Workpiece:SKD11
Speed:V=300m/min	Speed:V=80m/min
Feed per cutting edge:ft=0.1mm	Feed: Boring 0.07mm/rev., Fluting 0.15mm/t (per cutting edge)
Axial cutting depth: Ad=8mm	
Radial cutting depth: Rd=0.5mm	
Cutting oil: none	Cutting oil: none
Cutting distance: 150m	

[0097] [Table 20]

Test Sample No.	Cutting conditions I	Cutting conditions II
	Flank face wear (peripheral cutting edge, microns)	Maximum torque (N·cm)
8-1	42	680
8-2	21	430
8-3	35	510
8-4	85	1110 (Breakage during fluting)
8-5	121 (Chipping)	1050 (Breakage during fluting)

[0098] Based on the results, in the Test Samples 8-1 through 8-3, which have aluminum nitride layers with more than 0 and not more than 0.5 atomic percent of chlorine on the outermost layer as shown in Table 20 and predetermined inner TiCN film layers, wear was reduced and superior lubricity and improved fracturing resistance due to reduced cutting force was observed even in dry cutting. Because the Test Samples 8-1 - 8-3 were formed with a coating layer having superior lubricity, chip ejection qualities were good.

10 As a result, torque increases were limited and breaking resistance was improved, allowing problem-free cutting. With the Test Samples 8-4, 8-5, torque increased and breakage occurred when switching to slot milling. Furthermore, these Test Samples 8-1 - 8-3 provided superior welding resistance and peeling of the coating layer and the like did not take place.

15 Based on these factors, it could be seen that the Test Samples 8-1 - 8-3 were able to extend tool life.

[0099] (Test Example 2-5)

Substrates similar to those from the cemented carbide end mill

substrates used in the Test Example 2-4 were prepared. Thermal CVD was performed on locations associated with cutting, and coating layers were formed under the film forming conditions (gas composition, pressure, temperature) shown in Table 17. In this test, the following layers were formed, starting from the substrate side: TiN(0.5), columnar structure TiCN(4) or granular structure TiCN(4), TiBN(0.5), $\text{Al}_2\text{O}_3\text{-ZrO}_2(1)$; and an outermost layer formed from $\text{AlN}^{*1}(1.5)$ (Test Sample 8-3 from Table 18). The numbers in parentheses indicate film thickness in microns. Film thickness was controlled by controlling the film forming time. In this test, the aspect ratio and the face with the maximum index of orientation of the columnar structure TiCN film are varied, as shown in Table 17, by varying the film forming pressure and temperature as well as by varying the surface roughness and gas conditions for the TiN film formed below the TiCN film. More specifically, the aspect ratio of the TiCN film was set to at least 3, e.g., by using CH_3CN as the reaction gas, with the gas temperature set to 920 deg C and the pressure set to 6 kPa and the CH_3CN reaction gas being introduced gradually. Also, if the TiCN film maximum index of orientation TC is to be (422), for example, the surface roughness R_{max} (5 microns reference length) of the substrate is set to 0.09 microns and the TiCN film is formed while adjusting the aspect ratio outward from the substrate (away from the substrate). Furthermore, for all the test samples, the surface of the outermost layer was polished after forming the outermost layer so that the section of the outermost layer around the ridge line of the cutting edge that comes into contact with the workpiece had a surface

roughness Rmax of 0.4 microns for 5 microns reference length when measured by observing tool cross-sections. Table 21 shows TiCN film composition, aspect ratio, and the face with the maximum index of orientation TC.

[0100] [Table 21]

Test Sample No.	Inner layer TiCN film			Flank wear (outer perimeter, microns)
	Structure	Aspect ratio	Face with maximum TC	
9-1	Columnar	5.3	311	72
9-2	Columnar	6.8	422	64
9-3	Columnar	3.3	220	85
9-4	Columnar	2.4	220	140
9-5	Columnar	3.8	420	182
9-6	Granular	-	311	255(Chipping)

5

[0101] The surface-coated end mills with the coatings shown in Table 21 were used to perform side milling under the conditions described below, and wear for a fixed cutting length (80 m) was measured. Table 21 shows the results from the test as well.

10 [0102] End mill side milling

Workpiece: SKD11

Speed: V=250 m/min

Feed per cutting edge: ft=0.05 mm

Axial cutting depth: Ad=8 mm

15 Radial cutting depth: Rd=0.15 mm

Cutting oil: none Cutting length: 80 m

[0103] The results show that with a TiCN film as in Table 21, a columnar structure provides superior wear resistance. More specifically, with the Test Samples 9-1 - 9-3, which are formed with columnar structure TiCN

film at the inner layer with an aspect ratio of at least 3 and a maximum index of orientation of TC(311), TC(220), or TC(422), wear resistance is especially superior and tool life is longer, even when dry cutting. The reduced wear is believed to be because of the superior lubricity of the outermost layer and the
5 inner layer and the use of a predetermined TiCN film with superior wear resistance.

[0104] (Test Example 2-6)

Substrates similar to those from the cemented carbide end mill substrates used in the Test Example 2-4 were prepared. Thermal CVD was
10 performed on locations associated with cutting, and coating layers were formed under the film forming conditions (gas composition, pressure, temperature) shown in Table 17. In this test, the film forming conditions were controlled so that columnar structure TiCN films had an aspect ratio of at least 3 and the maximum index of orientation was TC(311), TC(220), or TC(422). Table 22
15 shows the composition, film thicknesses, and the film thickness of the entire coating layer (total film thickness). In Table 22, the films are indicated sequentially as the first film, the second film, and the like starting from the film closest to the substrate.

[0105] [Table 22]

Test Sample No.	First film		Second film		Third film		Fourth film		Fifth film		Sixth layer		Total thickness μm	Flank face wear μm
	Type	Thickness	Type	Thickness	Type	Thickness	Type	Thickness	Type	Thickness	Type	Thickness		
10-1	columnar TiCN	3.0	AIN ¹	1.0									4.0	52
10-2	columnar TiCN	0.5	ZrCN	7.0	AIN ¹	0.5							8.0	31
10-3	TiN	1.0	columnar TiCN	4.5	TiC	1.5	TiCNO	1.0	κ Al ₂ O ₃	3.0	AlCN ¹	5.0	16.0	34
10-4	TiN	0.3	columnar TiCN	6.5	TiBN	0.5	κ Al ₂ O ₃	1.5	TiN	0.3	AIN ¹	3.0	12.1	48
10-5	TiN	0.5	columnar TiCN	14.0	Al ₂ O ₃ /ZrO ₂	5.0	AIN ¹	2.0					21.5	26
10-6	columnar TiCN	3.0	TiZrCN	5.0	ZrO ₂	2.3	Al ₂ O ₃ /ZrO ₂	2.5	AlON ¹	1.7			14.5	44
10-7	columnar TiCN	3.2	TiN	0.5	HfCN	4.3	AlCN ¹	2.5					10.5	51
10-8	columnar TiCN	0.5	TiBN	1.3	α Al ₂ O ₃	5.0	AIN ¹	0.05					6.85	54
10-9	HfCN	3.5	α Al ₂ O ₃	1.5	TiCN ₀	2.3	columnar TiCN	6.5	TiN	0.7	AlCN ¹	0.7	15.2	38
10-10	columnar TiCN	5.0	TiZrCN	10.0	AlCN ¹	7.0							22	40
10-11	TiN	0.5	columnar TiCN	4.5	AlCN ¹	0.5	AIN ¹	0.5					6.0	48
10-12	TiN	0.5	TiCN ₀	2.0	columnar TiCN	6.0	TiBN	0.5	κ Al ₂ O ₃	1.5	AlCN ¹	0.7	11.2	53
10-13	columnar TiCN	2.0	HfCN	2.0	TiN	1.0							5.0	145
10-14	TiN	0.5	columnar TiCN	5.0	TiCN ₀	0.5	ZrO ₂	2.0	columnar TiCN	0.1	TiN	2.0	10.1	160
10-15	columnar TiCN	0.5	AlON ¹	2.0	α Al ₂ O ₃	3.0	TiN	1.5					7.0	136
10-16	columnar TiCN	0.07	AIN ¹	0.02									0.09	105
10-17	columnar TiCN	0.5	ZrCN	4.0	AIN ¹	0.02							4.52	98
10-18	TiN	0.5	columnar TiCN	3.0	TiCN ₀	9.0	α Al ₂ O ₃	3.5	Al ₂ O ₃ /ZrO ₂	5.0	AlCN ¹	8.0	29.0	102
10-19	columnar TiCN	4.0	TiBN	2.0	ZrO ₂	2.0	AlCN ¹	7.0					15.0	95
10-20	TiN	0.2	columnar TiCN	0.8	ZrCN	4.0	AlON ²	1.3					6.3	148
10-21	columnar TiCN	10.0	AlCN ¹	4.0									14.0	94

[0106] The surface-coated end mills with the coatings shown in Table 22 were used to perform side milling under the conditions described below, and

wear for a fixed cutting length (100 m) was measured. In this test, the flank face wear (microns) on the peripheral cutting edge was measured. Table 22 shows the results from the test as well.

[0107] End mill side milling

5 Workpiece: SUS304

Speed: $V=144$ m/min

Feed per cutting edge: $f_t=0.03$ mm

Axial cutting depth: $A_d=8$ mm

Radial cutting depth: $R_d=0.16$ mm

10 Cutting oil: none Cutting length: 100 m

[0108] As a result, it was found as shown in Table 22 that, compared to the other test samples, the Test Samples 10-1 - 10-12, 10-16 - 10-19, 10-21, which had an aluminum nitride film containing a predetermined amount of chlorine as the outermost layer and a columnar structure TiCN film inner layer with an aspect ratio of at least 3 and a maximum index of orientation of TC(311), TC(220), or TC(422), provided superior lubricity and superior wear resistance.

[0109] Also, the results shown in Table 22 indicate that it would be preferable for the outermost layer to be at least 0.03 microns and for the total film thickness to be at least 0.1 microns and no more than 24 microns. Furthermore, it can be seen that it would be preferable for the outermost layer to have no more than 1/2 the total thickness of the inner layer.

[0110] The end mills from the test sample 10-1 - 10-21 were all cut and

the surface roughness relative to a 5 micron reference length was measured for the area of the outermost layer near the ridge line of the cutting edge of the peripheral cutting edge that comes into contact with the workpiece. As a result, it was found that Rmax was no more than 1.3 microns for all inserts except the

5 Test Sample 10-21, while the Rmax of the Test Sample 10-21 was 1.6 microns. For the Test Sample 10-21, a #1500 diamond paste was used to polish the area of the outermost layer of the peripheral cutting edge near the ridge line of the cutting edge that comes into contact with the workpiece. When the method described above was used to measure surface roughness after polishing, Rmax

10 was 0.61 microns. When side milling was performed under the same cutting conditions using the polished end mill, the flank face wear was 48 microns. This is believed to be caused by a reduction in the cutting force resulting from less roughness at the area of the outermost layer near the ridge line of the cutting edge that comes into contact with the workpiece.

15 [0111] (Test Example 2-6')

Surface-coated end mills similar to those of the Test Samples 10-1 - 10-21 were prepared and cutting tests were performed under the cutting conditions described below. Crater wear (width) on the peripheral cutting edge was then measured for a predetermined cutting length (50 m).

20 The measurement of crater wear width was performed in a manner similar to that of the cutting test (Test Example 2-2') that used the surface-coated end mills from the Test Samples 7-1 - 7-23.

Workpiece: S50C

Speed: $V=120$ m/min

Feed: $f=0.05$ mm/t

Cutting depth: $A_d=10$ mm $R_d=0.6$ mm

Cutting oil: none (air blower) The results showed that the Test Samples

5 10-1 · 10-12, 10-16 · 10-19, and 10-21 had less crater wear compared to the other samples. For example, if the wear width of the Test Sample 7-14 from the Test Example 2-2' is defined as 1, the Test Samples 10-3, 10-6 had the values 0.39 and 0.42 respectively.

[0112] (Test Example 2-7)

10 Surface-coated end mills were prepared using the substrate described below with a widely known PVD method being used to form a coating layer having a composition similar to that of the Test Samples 10-2, 10-13 from Table 22. For the end mill with a coating layer having a composition similar to that of the Test Sample 10-2, the surface-coated end mill was formed by
15 adding chlorine to the outermost layer using ion implantation after the coating layer was formed. Then, side milling was performed using the same cutting conditions as the Test Example 2-6. The coating layers were all formed at areas associated with cutting.

The test samples with the coating layer from the Test Sample 10-2 all
20 had a chlorine content of 0.2 atomic percent on the outermost layer.

1 Brazed end mill substrate formed from cemented carbide corresponding to JIS Z20 (cutting section is cemented carbide)

2 Two-edge square end mill substrate formed from JIS-standard P20 cermet

(10 mm diameter)

3 Brazed ball mill formed from cubic boron nitride (Sumitomo Electric Hardmetal Corp. Ltd., BN300) (cutting section is cubic boron nitride)

5 The results indicated that all the surface-coated end mills formed with the coating layer from the Test Sample 10-2 provided superior lubricity and wear resistance. It was found that the tool life was at least twice that of end mills formed with the conventional coating layer from the Test Sample 10-13.

[Third Example]

[0113] The present invention will be described in further detail using
10 drills as an example.

(Test Example 3-1)

Solid drill substrates formed from cemented carbide corresponding to JIS K10 (8 mm diameter) were prepared. Thermal CVD, which is a chemical vapor deposition technique, was performed to form a coating layer on the
15 substrate at the surface of the areas (body) associated with cutting based on the film forming conditions from Table 12. In this test, the following layers were formed, starting from the substrate side: an inner layer formed from TiN(0.5), TiCN(4), TiBN(0.5), κ -Al₂O₃(1); and an outermost layer formed from AlN(1.5). The numbers in parentheses indicate film thickness in microns. Film
20 thickness was controlled by controlling the film forming time. Test samples in which the AlN film at the outermost layer have different chlorine contents were prepared by varying the film forming conditions as shown in Table 12. Table 23 shows chlorine content at the outermost layer. Specifically, samples

with more than 0 and no more than 0.5 atomic percent of chlorine, samples with more than 0.5 atomic percent of chlorine, and samples with no chlorine were prepared. Chlorine content was varied as shown in Table 12 by varying the proportion of hydrogen chloride (HCl) in the reaction gas. Also, using the amount of hydrogen chloride, the film forming pressure and the film forming temperature were varied as appropriate. Furthermore, the surface roughness at sites on the outermost layer near the ridge line of the cutting edge at areas that come into contact with the workpiece were studied for test samples containing more than 0 and no more than 0.5 atomic percent of chlorine in the outermost layer. Observation of the tool cross-sections showed that the Rmax for a reference length of 5 microns was no more than 1.3 microns for all samples. More specifically, the Rmax was 0.6 microns for Test Sample 11-2, for example. The chlorine content was measured using XPS (X-ray Photoelectron Spectroscopy). Also, the Knoop hardness for each of the layers in the test samples was studied, and it was found that in all cases the outermost AlN film was harder than the inner TiCN film layer.

[0114] [Table 23]

Test Sample No.	Outermost layer	Chlorine content (atomic percent)
11-1	AlN *1	0.03
11-2	AlN *1	0.18
11-3	AlN *1	0.48
11-4	AlN *2	0
11-5	AlN *3	0.98

[0115] Using the cutting conditions shown in Table 24, the cutting efficiency of the surface-coated drills with outermost layers as shown in Table

23 was observed. For cutting conditions 3, the number of holes bored until the tool broke was studied. For cutting conditions 4, the roundness of the holes was studied. The results of the tests are shown in Table 25.

[0116] [Table 24]

Cutting conditions 3	Cutting conditions 4
Drill boring (through-hole) Workpiece:SCM440 Speed:V=70m/min Feed:f=0.3mm/rev. Boring depth:40mm(L/D=5) Cutting oil:None (external air blower)	Drill boring (blind hole) Workpiece:NAK80 Speed:V=70m/min Feed:f=0.25mm/rev. Boring depth:40mm(L/D=5) Cutting oil: water soluble

5

[0117] [Table 25]

Test sample No.	Cutting conditions 3	Cutting conditions 4
	Number of holes before breakage	Roundness of hole entrance (microns)
11-1	At least 500 (no breaks)	3.5
11-2	At least 500 (no breaks)	2.1
11-3	At least 500 (no breaks)	2.8
11-4	285	13.8
11-5	182	15.9

[0118] Based on the results, in the Test Samples 11-1 through 11-3, which have aluminum nitride layers with more than 0 and not more than 0.5 atomic percent of chlorine on the outermost layer as shown in Table 25, and inner layers with films having predetermined compositions, superior chip ejection properties were provided and damage to the cutting section was reduced, allowing good cuts over an extended period of time. This significantly increased the number of cuts that could be made until the tool broke. This indicates that tool life was extended. For the Test Samples 11-1 - 11-3, it was found that the roundness of the bored holes was superior and that high-

10

15

precision cutting was possible. Furthermore, these Test Samples 11-1 - 11-3 provided superior welding resistance and peeling of the coating layer and the like did not take place.

[0119] (Test Example 3-2)

5 Substrates similar to those from the cemented carbide drill substrates used in the Test Example 3-1 were prepared. Thermal CVD was performed on the area associated with cutting, and coating layers were formed under the film forming conditions (gas composition, pressure, temperature) shown in Table 12 in the same manner as the coating layers indicated in Table 16.

10 [0120] The surface-coated drills with the coatings shown in Table 16 were used to perform boring operations under the conditions described below, and the number of holes bored until the tool life was reached was measured. The end of tool life was defined to be when flank face wear at the cutting section at the end reached 0.3 microns or when further cutting was not possible to tool breakage or the like. The results of the tests are shown in Table 26.

[0121] Drill boring (blind hole)

Workpiece: S50C

Speed: $V=100$ m/min

20 Feed: $f=0.2$ mm/rev.

Hole depth: 24 mm ($L/D=3$) Cutting oil: air blower

[0122] [Table 26]

Test Sample No.	Film structure	Number of holes bored during tool life	Test Sample No.	Film structure	Number of holes bored during tool life
12-1	7-1	3500	12-13	7-13	600
12-2	7-2	4500	12-14	7-14	790
12-3	7-3	5500	12-15	7-15	800
12-4	7-4	4000	12-16	7-16	1260
12-5	7-5	5000	12-17	7-17	1120
12-6	7-6	4000	12-18	7-18	1310
12-7	7-7	3500	12-19	7-19	1500
12-8	7-8	4000	12-20	7-20	800
12-9	7-9	4500	12-21	7-21	520
12-10	7-10	5500	12-22	7-22	1190
12-11	7-11	3500	12-23	7-23	1500
12-12	7-12	3500			

[0123] As a result, it was found as shown in Table 26 that, compared to the other test samples, the Test Samples 12-1 - 12-12, 12-16 - 12-19, 12-22, and 12-23, which had an aluminum nitride film containing a predetermined amount of chlorine as the outermost layer and films with predetermined compositions as the inner layers, provided superior lubricity and superior wear resistance.

[0124] Also, the results shown in Table 26 indicate that it would be preferable for the outermost layer to be at least 0.03 microns and for the total film thickness to be at least 0.1 microns and no more than 24 microns. Furthermore, it can be seen that it would be preferable for the outermost layer to have no more than 1/2 the total thickness of the inner layer.

[0125] The end mills from the test sample 12-1 - 12-23 were all cut and the surface roughness relative to a 5 micron reference length was measured for the area of the outermost layer near the ridge line of the cutting edge of the

peripheral cutting edge that comes into contact with the workpiece. As a result, it was found that R_{max} was no more than 1.3 microns for all inserts except the Test Sample 12-22, while the R_{max} of the Test Sample 12-22 was 1.9 microns. For the Test Sample 12-22, as in the Test Sample 7-22, a #1500 diamond paste
5 was used to polish the area of the outermost layer of the peripheral cutting edge near the ridge line of the cutting edge that comes into contact with the workpiece. When the method described above was used to measure surface roughness after polishing, R_{max} was 0.45 microns. When boring was performed under the same cutting conditions using the polished drill, the
10 number of operations performed was 4500. This is believed to be caused by a reduction in the cutting force resulting from less roughness at the area of the outermost layer near the ridge line of the cutting edge that comes into contact with the workpiece. When the surface roughness of the Test Sample 12-1 was measured as described above, the R_{max} was 0.78 microns, but when the
15 cutting edge was polished in the same manner, the cut count after another boring operation was found to be significantly improved, at 5000.

[0126] Furthermore, a coating film was formed on the Test Sample 12-23 to make the film hardness of the inner layer higher than that of the outermost layer. Then, the hardnesses of the films forming the coating layers of the Test
20 Samples 12-1 - 12-20, 12-22, and 12-23 were measured. The film hardness of the outermost layer was lower than that of at least one film of the inner layer for all the drills, with the exception of Test Sample 12-23. With the Test Sample 12-23, the film hardness of the outermost layer was higher than that of

the inner layer. Based on this, it is believed that the cutting efficiency of the Test Sample 12-23 was reduced compared to the Test Samples 12-1 - 12-12.

[0127] (Test Example 3-2')

Surface-coated drills similar to those of the Test Samples 12-1 - 12-23
 5 were prepared and cutting tests were performed under the cutting conditions described below. Crater wear (width) was then measured for a predetermined number of holes (500 holes). Measurements were made on the widths of crater wear near the center of the cutting section. Measurements were performed in a manner similar to those of the Test Example 2-2'.

10 Results were evaluated based on these measurements by comparing the different test samples.

Workpiece: S50C (blind hole)

Speed: $V=70$ m/min

Feed: $f=0.25$ mm/rev.

15 Hole depth: 40 mm ($L/D=5$)

Cutting oil: mist (soluble cutting fluid) The results showed that the Test Samples 12-1 - 12-12, 12-16 - 12-19, 12-22, and 12-23 had less crater wear compared to the other samples. For example, if the wear width of the Test Sample 12-14 is defined as 1, the Test Samples 12-3, 12-9 had the values 0.32
 20 and 0.38 respectively.

[0128] (Test Example 3-2'')

In the above test, dry cutting was performed. In this test, drills similar to those of the Test Samples 12-1 - 12-23 were prepared, and boring counts

were measured as in the above test under the following boring conditions: 40 mm boring depth ($L/D=5$); and cutting oil: instead of using an air blower, wet cutting, and mist cutting were used. As a result, it was found the Test Samples which had a aluminum nitride film containing a predetermined amount of chlorine as the outermost layer and films with predetermined compositions as the inner layers provided superior lubricity, superior wear resistance, and longer tool life.

[0129] (Test Example 3-3)

Surface-coated drills were prepared using the substrate described below with a widely known PVD method being used to form a coating layer having a composition similar to that of the Test Samples 7-2, 7-13 from Table 16. For the drill with a coating layer having a composition similar to that of the Test Sample 7-2, the surface-coated end mill was formed by adding chlorine to the outermost layer using ion implantation after the coating layer was formed. Then, boring (blind hole) was performed using the same cutting conditions (dry cutting) as the Test Example 3-2. The coating layers were all formed at areas associated with cutting.

Also, for the test samples on which the coating layer from the Test Sample 7-2 were formed, the chlorine content at the outermost layer was set to 0.2 atomic percent.

1 High speed tool steel drill substrate (solid)

The results indicated that all the surface-coated drills formed with the coating layer from the Test Sample 7-2 provided superior lubricity and wear

resistance. It was found that the tool life was at least three times that of end mills formed with the conventional coating layer from the Test Sample 7-13.

[0130] (Test Example 3-4)

Solid drill substrates formed from cemented carbide corresponding to

5 JIS K10 (8 mm diameter) were prepared. Thermal CVD, which is a chemical vapor deposition technique, was performed to form a coating layer on the substrate at the surface of the areas (body) associated with cutting based on the film forming conditions from Table 17. In this test, the following layers were formed, starting from the substrate side: an inner layer formed from

10 TiN(0.5), columnar structure TiCN(4), TiBN(0.5), κ -Al₂O₃(1); and an outermost layer formed from AlN(1.5). The numbers in parentheses indicate film thickness in microns. Film thickness was controlled by controlling the film forming time. In this test, the TiCN film was grown so that it has a columnar structure with an aspect ratio of 4.2 and so that the (311) plane has the

15 maximum index of orientation TC. More specifically, the TiN film formation conditions (gas composition, pressure, temperature) were set up so that the reaction gas was CH₃CN, the temperature was 900 deg C, the pressure was 8 kPa, and the surface roughness R_{max} (5 microns reference length) of the TiN film formed below the TiCN film was 0.1 microns. Test samples in which the

20 AlN film at the outermost layer have different chlorine contents were prepared by varying the film forming conditions as shown in Table 17. Table 27 shows chlorine content at the outermost layer. Specifically, samples with more than 0 and no more than 0.5 atomic percent of chlorine, samples with more than 0.5

atomic percent of chlorine, and samples with no chlorine were prepared. Chlorine content was varied as shown in Table 17 by varying the proportion of hydrogen chloride (HCl) in the reaction gas. Also, using the amount of hydrogen chloride, the film forming pressure and the film forming temperature were varied as appropriate. Furthermore, the surface roughness at sites on the outermost layer near the ridge line of the cutting edge at areas that come into contact with the workpiece were studied for test samples containing more than 0 and no more than 0.5 atomic percent of chlorine in the outermost layer. Observation of the tool cross-sections showed that the Rmax for a reference length of 5 microns was no more than 1.3 microns for all samples. More specifically, the Rmax was 0.6 microns for Test Sample 13-2, for example. The chlorine content was measured using XPS (X-ray Photoelectron Spectroscopy).

[0131] [Table 27]

Test sample No.	Outermost layer	Chlorine content (atomic %)
13-1	AlN *1	0.03
13-2	AlN *1	0.18
13-3	AlN *1	0.48
13-4	AlN *2	0
13-5	AlN *3	0.98

[0132] Using the cutting conditions shown in Table 28, the cutting efficiency of the surface-coated drills with outermost layers as shown in Table 27 was observed. For cutting conditions III, the number of holes bored until the tool broke was studied. For cutting conditions IV, the roundness of the holes was studied. The results of the tests are shown in Table 29.

[0133] [Table 28]

Cutting conditions III	Cutting conditions IV
Drill boring (through-hole)	Drill boring (blind hole)
Workpiece:SCM440	Workpiece:NAK80
Speed:V=70m/min	Speed:V=70m/min
Feed:f=0.3 mm/rev.	Feed:f=0.25mm/rev.
Boring depth:40mm(L/D=5)	Boring depth:40mm(L/D=5)
Cutting oil: none (external air blower)	Cutting oil: water soluble

[0134] [Table 29]

Test Sample No.	Cutting conditions III	Cutting conditions IV
	Number of holes before breakage	Roundness of hole entrance (microns)
13-1	At least 500 (no breaks)	3.8
13-2	At least 500 (no breaks)	1.9
13-3	At least 500 (no breaks)	3.1
13-4	312	15.3
13-5	250	12.1

- 5 [0135] Based on the results, in the Test Samples 13-1 through 13-3, which have aluminum nitride layers with more than 0 and not more than 0.5 atomic percent of chlorine on the outermost layer as shown in Table 29, and predetermined inner TiCN film layers, superior chip ejection properties were provided and damage to the cutting section was reduced, allowing good cuts
- 10 over an extended period of time. This significantly increased the number of cuts that could be made until the tool broke. This indicates that tool life was extended. For the Test Samples 13-1 - 13-3, it was found that the roundness of the bored holes was superior and that high-precision cutting was possible. Furthermore, these Test Samples 13-1 - 13-3 provided superior welding
- 15 resistance and peeling of the coating layer and the like did not take place.

[0136] (Test Example 3-5)

Substrates similar to those from the cemented carbide drill substrates used in the Test Example 3-4 were prepared. Thermal CVD was performed on the area associated with cutting, and coating layers were formed under the film forming conditions (gas composition, pressure, temperature) shown in Table 17. In this test, the following layers were formed, starting from the substrate side: TiN(0.5), columnar structure TiCN(4) or granular structure TiCN(4), TiBN(0.5), $\text{Al}_2\text{O}_3\text{-ZrO}_2(1)$; and an outermost layer formed from $\text{AlN}^{*1}(1.5)$ (Test Sample 8-3 from Table 18). The numbers in parentheses indicate film thickness in microns. Film thickness was controlled by controlling the film forming time. In this test, the aspect ratio and the face with the maximum index of orientation of the columnar structure TiCN film are varied, as shown in Table 17, by varying the film forming pressure and temperature as well as by varying the surface roughness and gas conditions for the TiN film formed below the TiCN film. More specifically, the aspect ratio of the TiCN film was set to at least 3, e.g., by using CH_3CN as the reaction gas, with the gas temperature set to 920 deg C and the pressure set to 6 kPa and the CH_3CN reaction gas being introduced gradually. Also, if the TiCN film maximum index of orientation TC is to be (422), for example, the surface roughness R_{max} (reference length) of the substrate is set to 0.09 microns and the TiCN film is formed while adjusting the aspect ratio outward from the substrate (away from the substrate). Furthermore, for all the test samples, the surface of the outermost layer was polished after forming the outermost layer so that the section of the outermost layer around the ridge line of the cutting

edge that comes into contact with the workpiece had a surface roughness R_{\max} of 0.4 microns for 5 microns reference length when measured by observing tool cross-sections. Table 30 shows TiCN film composition, aspect ratio, and the face with the maximum index of orientation TC.

5 [0137] [Table 30]

Test Sample No.	Inner layer TiCN film			Number of holes bored during tool life
	Structure	Aspect ratio	Face with maximum TC	
14-1	Columnar	5.1	311	800
14-2	Columnar	7.0	422	920
14-3	Columnar	3.2	220	900
14-4	Columnar	2.1	220	250
14-5	Columnar	4.0	420	210
14-6	Granular	-	311	330

[0138] The surface-coated drills with the TiCN films shown in Table 30 forming an inner layer were used to perform boring operations under the conditions described below, and the number of holes bored until the tool life was reached was measured. The end of tool life was defined to be when flank face wear at the cutting section at the end reached 0.3 microns or when further cutting was not possible to tool breakage or the like. Table 30 shows the results from the test as well.

[0139] Drill Boring (Through-hole)

15 Workpiece: S50C

Speed: $V=80$ m/min

Feed: $f=0.2$ mm/rev.

Hole depth: 40 mm ($L/D=5$) Cutting oil: mist (soluble cutting fluid)

[0140] The results show that with a TiCN film as in Table 30, a columnar structure provides superior wear resistance. More specifically, with the Test Samples 14-1 - 14-3, which are formed with columnar structure TiCN film at the inner layer with an aspect ratio of at least 3 and a maximum index of orientation of TC(311), TC(220), or TC(422), wear resistance is especially superior and tool life is longer, even when dry cutting. The longer tool life is believed to be because of the superior lubricity of the outermost layer and the inner layer and the use of a predetermined TiCN film with superior wear resistance.

10 [0141] (Test Example 3-6)

Substrates similar to those from the cemented carbide drill substrates used in the Test Example 3-4 were prepared. Thermal CVD was performed on the area associated with cutting, and coating layers were formed under the film forming conditions (gas composition, pressure, temperature) shown in Table 17 in the same manner as the coating layers shown in Table 22. In this test, as in the Test Example 2-6, the film forming conditions were controlled so that columnar structure TiCN films had an aspect ratio of at least 3 and the maximum index of orientation was TC(311), TC(220), or TC(422).

[0142] The surface-coated drills with the coatings shown in Table 22 were used to perform boring operations under the conditions described below, and the number of holes bored until the tool life was reached was measured. The end of tool life was defined to be when flank face wear at the cutting section at the end reached 0.3 microns or when further cutting was not

possible to tool breakage or the like. The results of the tests are shown in Table 31.

[0143] Drill boring (blind hole)

Workpiece: S50C

5 Speed: $V=120$ m/min

Feed: $f=0.2$ mm/rev.

Hole depth: 24 mm ($L/D=3$) Cutting oil: air blower

[0144] [Table 31]

Test Sample No.	Film structure	Number of holes bored during tool life	Test Sample No.	Film structure	Number of holes bored during tool life
15-1	10-1	4000	15-13	10-13	820
15-2	10-2	4500	15-14	10-14	600
15-3	10-3	5000	15-15	10-15	800
15-4	10-4	4500	15-16	10-16	1050
15-5	10-5	5500	15-17	10-17	1420
15-6	10-6	4500	15-18	10-18	1330
15-7	10-7	3500	15-19	10-19	1200
15-8	10-8	4000	15-20	10-20	510
15-9	10-9	4000	15-21	10-21	1010
15-10	10-10	5500			
15-11	10-11	4000			
15-12	10-12	4500			

10 [0145] As a result, it was found as shown in Table 31 that the Test Samples 15-1 - 15-12, 15-16 - 15-19, 15-21, which had an aluminum nitride film containing a predetermined amount of chlorine as the outermost layer and a columnar structure TiCN film inner layer with an aspect ratio of at least 3 and a maximum index of orientation of TC(311), TC(220), or TC(422), provided
 15 superior lubricity and superior wear resistance compared to the Test Samples 15-13 - 15-15, 15-20, which correspond to conventional technologies.

[0146] Also, the results shown in Table 31 indicate that it would be preferable for the outermost layer to be at least 0.03 microns and for the total film thickness to be at least 0.1 microns and no more than 24 microns. Furthermore, it can be seen that it would be preferable for the outermost layer
5 to have no more than 1/2 the total thickness of the inner layer.

[0147] The end mills from the test sample 15-1 - 15-21 were all cut and the surface roughness relative to a 5 micron reference length was measured for the area of the outermost layer near the ridge line of the cutting edge of the peripheral cutting edge that comes into contact with the workpiece. As a result,
10 it was found that Rmax was no more than 1.3 microns for all inserts except the Test Sample 15-21, while the Rmax of the Test Sample 15-21 was 2.0 microns. For the Test Sample 15-21, as in the Test Sample 10-21, a #1500 diamond paste was used to polish the area of the outermost layer of the peripheral cutting edge near the ridge line of the cutting edge that comes into contact
15 with the workpiece. When the method described above was used to measure surface roughness after polishing, Rmax was 0.52 microns. When boring was performed under the same cutting conditions using the polished drill, the number of operations performed was 4000. This is believed to be caused by a reduction in the cutting force resulting from less roughness at the area of the
20 outermost layer near the ridge line of the cutting edge that comes into contact with the workpiece.

[0148] (Test Example 3-6')

Surface-coated drills similar to those of the Test Samples 15-1 - 15-21

were prepared and cutting tests were performed under the cutting conditions described below. Crater wear (width) was then measured for a predetermined number of holes (500 holes).

5 The measurement of crater wear width was performed in a manner similar to that of the cutting test (Test Example 3-2') that used the surface-coated end mills from the Test Samples 12-1 · 12-23.

Workpiece: S50C (stopping hole)

Speed: $V=100$ m/min

Feed: $f=0.25$ mm/rev.

10 Hole depth: 40 mm ($L/D=5$)

Cutting oil: mist (soluble cutting fluid) The results showed that the Test Samples 15-1 · 15-12, 15-16 · 15-19, and 15-21 had less crater wear compared to the other samples. For example, if the wear width of the Test Sample 12-14 from the Test Example 3-2' is defined as 1, the Test Samples 15-3, 15-9 had the values 0.29 and 0.35 respectively.

[0149] (Test Example 3-6")

In the above test, dry cutting was performed. In this test, drills similar to those of the Test Samples 15-1 · 15-21 were prepared, and boring counts were measured as in the above test under the following boring conditions: 40 mm boring depth ($L/D=5$); and cutting oil: wet cutting, mist cutting with air blower. As a result, it was found that the test samples, which had an aluminum nitride film containing a predetermined amount of chlorine as the outermost layer and a columnar structure TiCN film inner layer with an

aspect ratio of at least 3 and a maximum index of orientation of TC(311), TC(220), or TC(422), provided superior lubricity and superior wear resistance as well as long tool life.

[0150] (Test Example 3-7)

5 Surface-coated drills were prepared using the substrate described below with a widely known PVD method being used to form a coating layer having a composition similar to that of the Test Samples 10-2, 10-13 from Table 22. For the drill with a coating layer having a composition similar to that of the Test Sample 10-2, the surface-coated end mill was formed by adding chlorine to the
10 outermost layer using ion implantation after the coating layer was formed. Then, boring (blind hole) was performed using the same cutting conditions (dry cutting) as the Test Example 3-6. The coating layers were all formed at areas associated with cutting.

Also, for the test samples on which the coating layer from the Test
15 Sample 10-2 were formed, the chlorine content at the outermost layer was set to 0.2 atomic percent.

1. High speed tool steel drill substrate (solid)

The results indicated that all the surface-coated drills formed with the coating layer from the Test Sample 10-2 provided superior lubricity and wear
20 resistance. It was found that the tool life was at least three times that of end mills formed with the conventional coating layer from the Test Sample 10-13.

Industrial Applicability

[0151] The surface-coated cutting tool of the present invention is suited for cutting under harsh conditions, e.g., cutting involving high temperatures for the cutting edge such as dry cutting, mist cutting, and intermittent cutting, boring, and cutting of workpieces that tend to weld easily.

Also, the surface-coated cutting tool of the present invention is suited for cutting steel and the like under conditions that tend to lead to welding.

Brief Description of Drawings

10 [0152] Fig. 1 (A) is a simplified front-view drawing of an end mill. Fig. 1 (B) is a simplified front-view drawing of a drill.

[List of designators]

[0153] 1: end cutting edge; 2: peripheral cutting edge; 3, 7: flute; 4, 8: body; 5, 9: shank; 6: tip